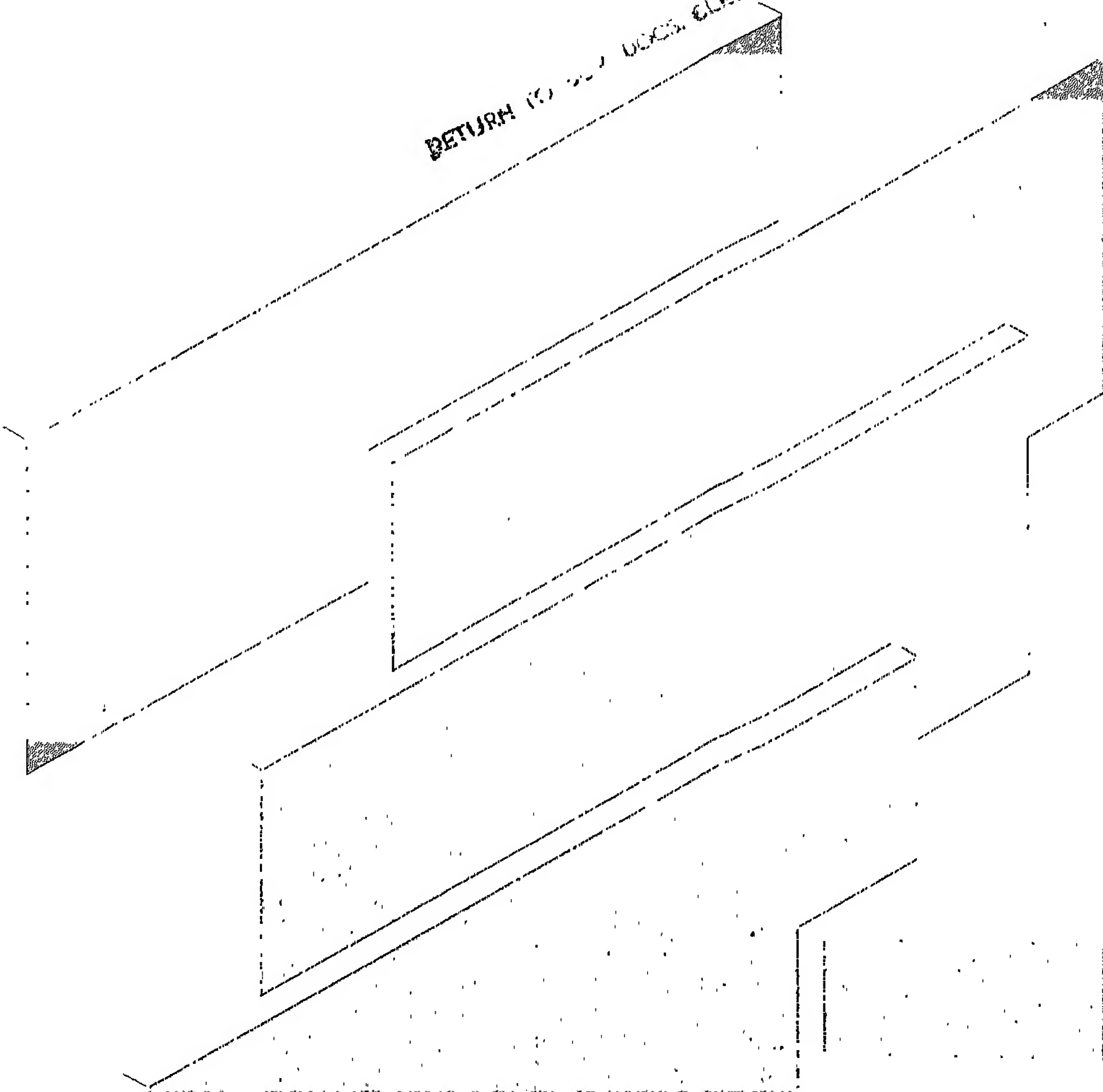
U.S. Department of Housing and Urban Development
Office of Policy Development and Research

Design and Construction of Large-Panel Concrete Structures

Supplemental Report C "Seismic Tests of Horizontal Joints"



DESIGN AND CONSTRUCTION OF LARGE PANEL CONCRETE STRUCTURES

Contract No. H-2131R

supplemental report C

Seismic Tests of Horizontal Joints

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FOREWORD

Traditionally, multi-story buildings are so constructed that if a load-carrying member collapses, the entire structure does not: it has an inherent structural integrity. But construction using large-panel concrete members is not traditional. Builders cannot necessarily depend on the new structure's inherent integrity.

To avoid potential problems, the Office of Policy Development and Research has undertaken an extensive research program on large-panel concrete structures. This report, the seventh of nine, concerns itself with testing the resistance of large-panel structures to earthquake loadings.

The research program was supervised for HUD by the late William J. Werner and continued by Ronald J. Morony. Designers, manufacturers, and builders have reason to be grateful to them.

Donna E. Shalala
Assistant Secretary for Policy
Development and Research

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ABSTRACT

This report describes preliminary tests to investigate the force versus deformation characteristics of a horizonal joint in a large panel building subjected to simulated seismic loading. Shear stress produced by an earthquake may exceed the capacity of the horizontal joint and produce slip at the joint. These tests revealed a low friction coefficient. A load-slip relationship that may be used in analysis of buildings for seismic resistance is presented.

EXECUTIVE SUMMARY

This report on an experimental investigation of seismic resistance is the third of three Supplemental Reports leading to the development of a "Methodology for the Design and Construction of Large Panel (LP) Structures." The objective of this report is to present factual data and conclusions relating to the resistance of LP structures to earthquake loadings.

Five full-scale joints were tested under simulated seismic movements that caused the joint to slide in the plane of the wall. The purpose was to determine the coefficient of friction for extremely smooth joint surfaces with different magnitudes of vertical loads on the wall. Vertical ties were placed in two test specimens.

Test results indicated a variation in the coefficient of friction from a minimum of 0.2 to a maximum of 0.4 for the smooth surfaces used on the wall ends at the joint. The minimum value was associated with joints undamaged by repeated sliding up to a displacement of 0.6 in. (15 mm). A rectangular stable shear-displacement loop was obtained when no tie was used in the joint. Localized concentration of shear resistance at a vertical tie through the joint caused severe damage to the grouted joint portion between the slab ends. Cracking and crushing of the grout disturbed shear transfer. Padding on a vertical tie reduced the damage to minor local crushing of the grout at the edge of the tie. A tie in the joint produced a shear-displacement loop that was shaped like a parallelogram.

These data can be used in the dynamic seismic analysis of LP structures.

OVERALL PROGRAM OBJECTIVES

The term "large panel" (LP) concrete structure is used to describe a structural system composed of precast vertical wall panels with precast floors and roofs of panels or planks (Fig. 1). These prefabricated component buildings can be considered to be the industrialized form of conventional cast-in-place structural wall (egg crate) construction. Large panel buildings are differentiated by the general arrangement (Fig. 2) of load-bearing walls:

(a) Cross wall system: in this most prevalent form, the load-bearing cross walls are perpendicular to the longitudinal axis of the building.

(b) Spine wall system: the load-bearing walls are parallel to the longitudinal axis of the structure.

(c) Mixed systems: a combination of cross wall and spine wall systems.

In most LP systems, the walls transfer their loads directly to the substructure without an intermediate frame. This form of construction restricts open plans at any level and is typically suited for multistory housing where walls of substance usually have to be provided between dwelling units to ensure fire resistance and noise suppression. Types of construction considered in this investigation include solid, sandwich, ribbed, hollow core or composite wall panels; and solid, hollow core, or ribbed floor units with or without cast-in-place topping. All elements can be either prestressed or conventionally reinforced.

The overall program objective is to develop minimum criteria for the design and construction of large panel structures. These criteria are being developed to ensure the structural safety and serviceability of LP residential buildings, and provide minimum performance requirements to be used by designers and developers of innovative systems. The development of the criteria also will expand the knowledge of design and construction of large panel structures to a level comparable to that of conventional cast-in-place concrete or steel structural systems.

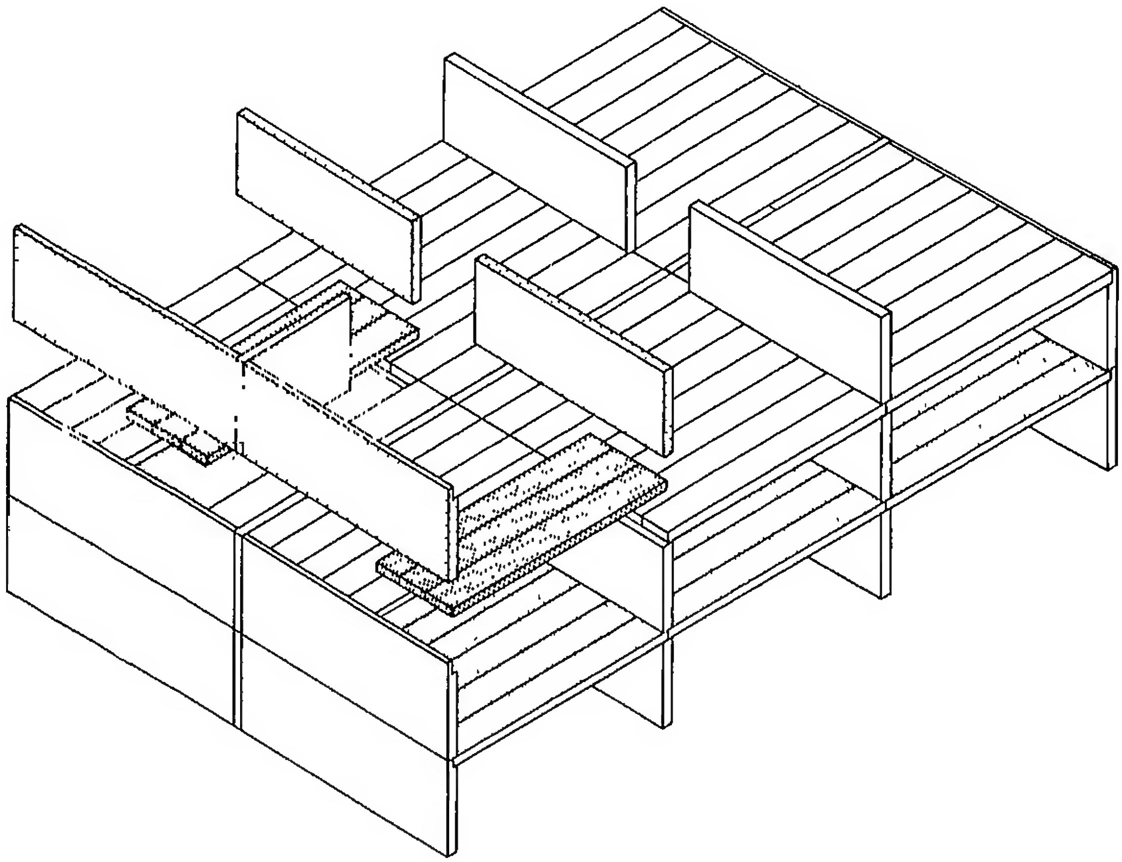
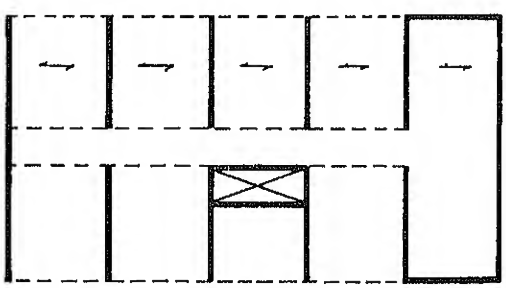
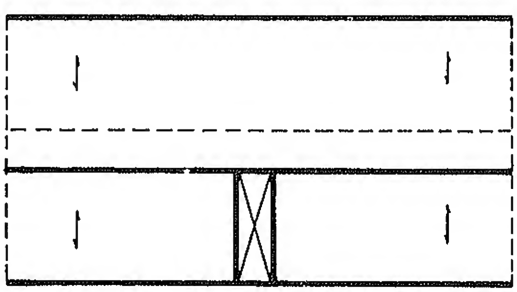


Fig. 1 Isometric View of Idealized Large Panel Structure



(a) Cross Wall System



(b) Spine Wall System

Fig. 2 Idealized Arrangement of Structural Wall Panels in Large Panel Structures

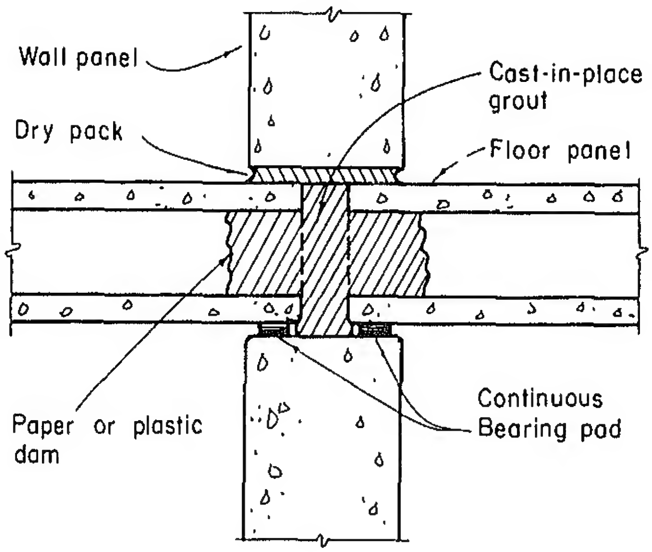
1. INTRODUCTION

This report describes tests conducted in a major investigation concerned with the development of criteria for design and construction of large panel structures. Tests were carried out to investigate the force-deformation characteristics of the horizontal floor-wall joint subject to repeated reversals of shear forces applied along the joint.

A large panel building may be described as a "shear wall" structure if the wall panels and their connections have sufficient strength to match their rigidity(1). For resistance to wind loading, it is reasonable to assume the wall assemblies act monolithically since shear stresses in the connections have a reasonably low magnitude(2). Higher shear stresses produced by an earthquake may exceed the capacity of the horizontal joint and produce slip at one or more floor levels of a building. Analysis of the structural wall building with non-rigid horizontal joints requires information on force-deformation characteristics of the joints for repeated cycles of shear loading.

An interior horizontal joint is shown in Fig. 3. Sliding planes due to shear could occur at three surfaces. One location is below the floor panels where the bearing pads and cast-in-place grout rest on top of the lower wall. The second location is at the top of the joint where the dry pack is cast against the top surface of the floor panels and on top of the cast-in-place grout. The third location is above the dry pack and at the bottom of the upper wall. Wall panels precast in factory steel forms have extremely smooth edges. The usual rough top surface of the slabs, as compared to the smooth ends of the wall, would force the slip plane to occur at the wall-joint interfaces.

Shear transfer depends on cohesion, friction, and dowel action. Cohesion or bond at the interface has an influence on the initial value of shear prior to initial slip. After initial slip, the force level with continued sliding depends on a normal force across the interface to develop a frictional resistance. The frictional resistance will be also related to surface roughness. Dowel action at a vertical tie through the joint will augment



(Ties not shown)

Fig. 3 Interior Wall-to-Floor Connection

resistance in proportion to the amount of slip. Increased slip movement will produce increased bearing stress and deformation at the tie resulting in increased shear resistance.

Several experimental investigations have been conducted to study friction for a single loading. Although the literature does not provide information on the repeated reversals of shear as required for seismic analysis, the data provide a base line for comparison.

Jones[(3)] tested the shear strength at joints between precast pieces held together by a central post-tensioned rod. The 4x6-in. (100x150 mm) contact surfaces were cast against steel forms. Minimum coefficient of friction for plain butt joints was found to be 0.391 and for mortared joints this value was 0.645. The pressure holding the joints together was varied from 100 to 3000 psi (0.7 to 21 MPa) on the contact surface. Data from these tests are shown in Fig. 4. Consistent results were obtained even though repeated tests were performed on specimens to produce initial slip. This indicates that no damage was done to the mating surfaces by several repetitions of shear loading to initial slip. Three similar tests with mortar bonding between the two blocks are plotted also in Fig. 4. Mortar bonding increases the load at first slip.

Franz[(4)] also determined shear strength at joints between precast pieces. The rods for applying normal stress to his specimens were outside the 8x8-in. (200x200 mm) cross-section. The minimum coefficient of friction was 0.77. Four data points, shown in Fig. 4, represent smooth joints without mortar. These data were considerably higher than Jones' data for similar specimens. Concrete strength was about 4000 psi (28 MPa) as compared to an estimated 6500 psi (45 MPa) for concrete used by Jones.

Gaston and Kriz[(5)] also tested the shear strength at joints between precast pieces. Rods for applying normal stress to their specimens were passed through oversized holes in the 10x10-1/2-in. (254x267 mm) or by 10x5-1/4-in. (254x133 mm) cross-sections. Data points for normal stress up to 1000 psi (6.9 MPa) are shown in Fig. 4. For these specimens, the minimum coefficient of friction was 0.79 with a concrete strength estimated at 5000 psi (35 MPa).

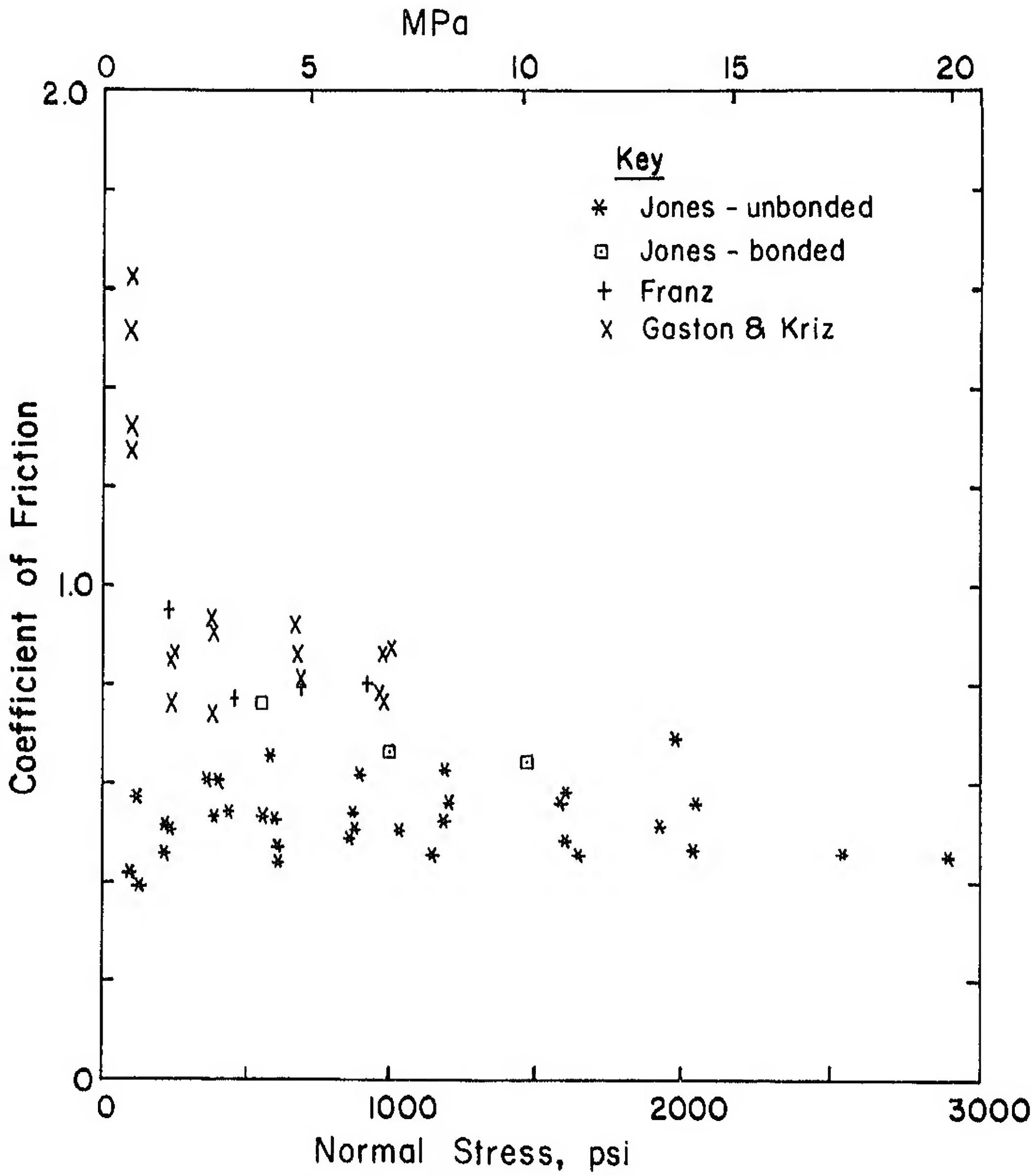


Fig. 4 Published Friction Data

Based on the data shown in Fig. 4, care should be exercised in selecting a coefficient of friction for a large panel joint subject to shear load. The value is between 0.4 and 0.9 for a normal stress of 1000 psi (6.9 MPa). The reason for the wide variation is not discussed by any of the authors. Each set of data is very consistent. Texture of the sliding surface is probably consistent in each of these works but texture may be the major difference between the test groups. Jones specimens were cast against steel forms to give a very smooth surface. Gaston and Kriz cast their specimens against cold rolled steel plates or plastic-coated plywood. Although these would appear to be similar in smoothness, the results by Jones are at the low end of the range while those from Gaston and Kriz are at the high end. It is possible that the unmentioned release agent used on the forms caused the very important difference.

Information on the character of the shear versus displacement relationship for repeated reversals of movement was not presented in earlier works. Therefore, in this program, test specimens were made and loaded to develop preliminary information on the response of interior horizontal joints to simulated cyclic earthquake loading. The primary variable was the level of vertical load through the joint. Some specimens included a vertical tie through the joint. The test results include force versus displacement for repeated reversal of shear causing slip of the joint. The edge surfaces of the walls were cast against plastic-coated plywood to produce a smooth surface for sliding in the joint.

2. EXPERIMENTAL PROGRAM

Two different test specimens were used. Each consisted of an assembly of pieces to form a joint in the manner shown in Fig. 3. The first specimen consisted of a 4-ft long (1.22 m) section of joint. The remaining specimens consisted of a 2-ft long (609 mm) section of joint. In each case, the formed surface of the end of the wall at the joint was intentionally made extremely smooth to test an extreme situation.

2.1 Long-Joint Specimen

A simplified outline of the cross-section of the long joint is shown in Fig. 5. Precast concrete sections were used for the walls and floor slab. Details of manufacture and assembly are given in Appendices B.1 and B.2.

The long-joint specimen was designated S1 for identification purposes.

End brackets were built onto the walls to allow shear loading at the mid height of the joint. Brackets were built onto the top and bottom of the walls to enable application of the normal force or wall load. Hydraulic rams were used to apply 268.8 kips (1195 kN) of load. This is equivalent to 700 psi (4.8 MPa) on the gross area of wall.

The specimen was turned 90° and placed in a million pound capacity testing machine. The 4-ft (1.22 m) length of the joint was then vertical and centered in the machine as shown in Fig. 6. End bearing plates were placed to enable the test machine to push the joint in one direction for the first half of a load cycle. Bearing plates were replaced to push the joint in the opposite direction to complete a cycle of load. The complete test consisted of the following cycles of displacement in each direction, applied in sequential order:

(a) three cycles to 0.1-in. (2.5 mm) displacement,
(b) nine cycles to 0.2-in. (5.1 mm) displacement, and
(c) three or more cycles to at least 0.3-in. (7.6 mm) displacement.

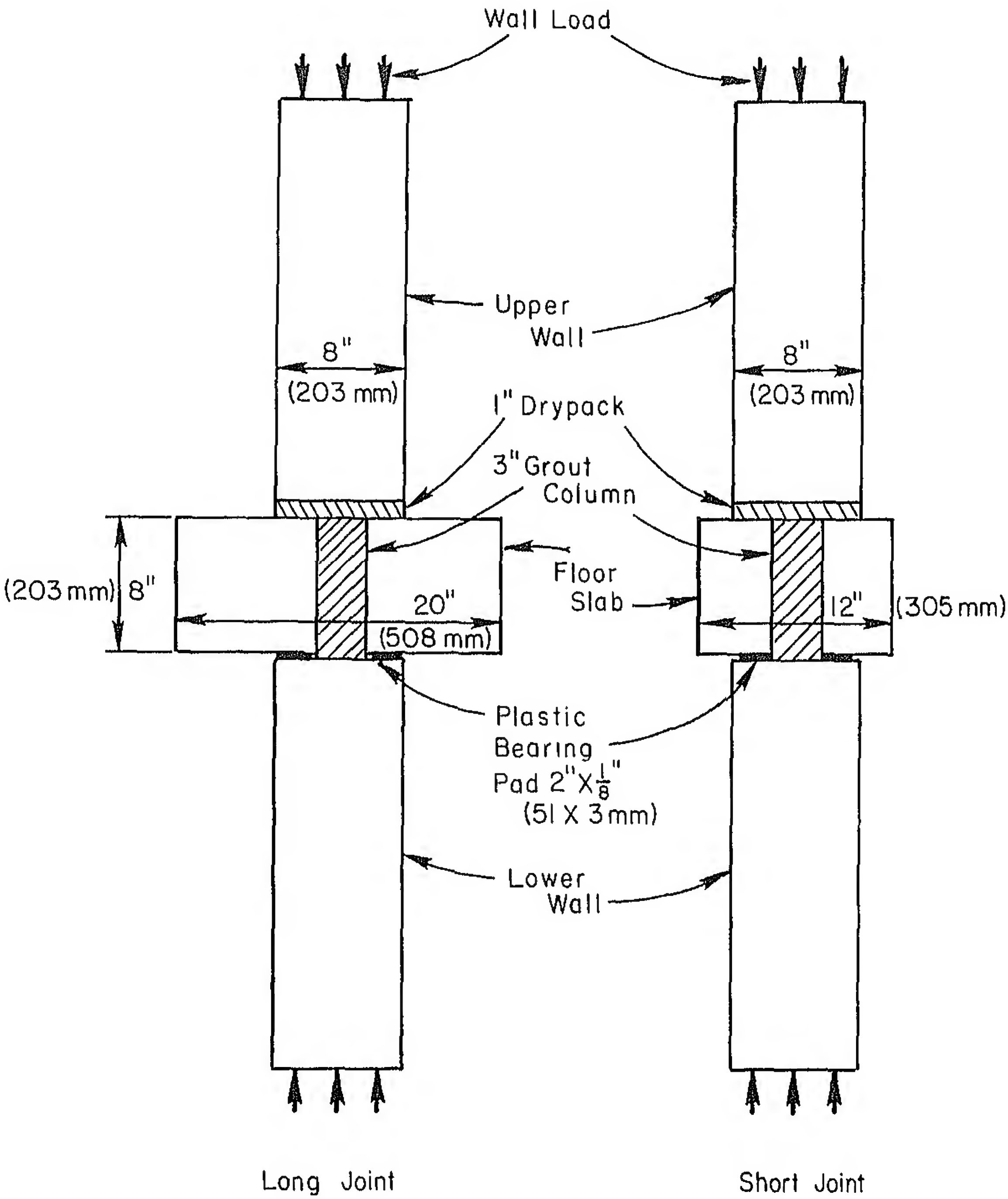


Fig. 5 Cross-sections of Test Specimens

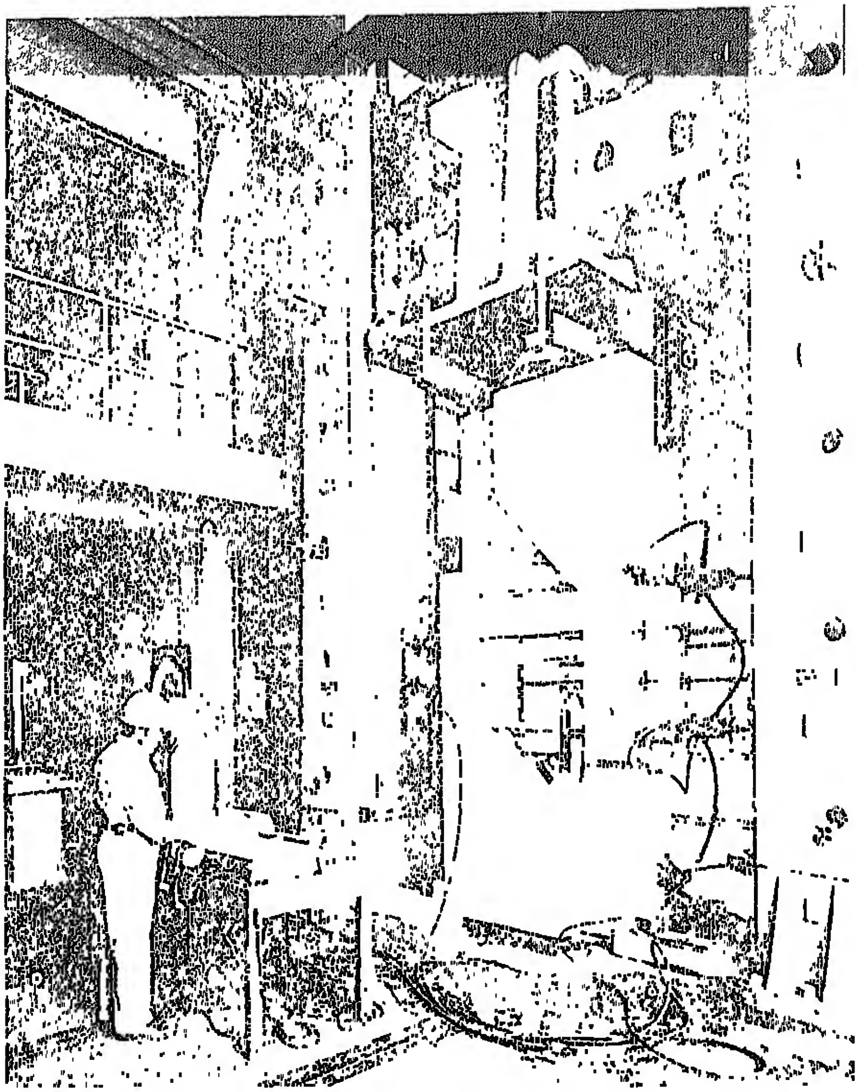


Fig. 6 Test Setup for Long-Joint Specimen

The normal force or wall load was held constant throughout the entire cyclical sequence.

2.2 Short-Joint Specimens

A simplified outline of the cross-section of the short-joint specimen is shown in Fig. 5. Details of the precast parts, manufacture and assembly are presented in Appendices B.1 and B.2. End brackets were built onto the upper wall to allow shear loading at mid height of the joint. A cross frame was built onto the lower wall. Hydraulic rams were located for applying shear load and normal wall force as shown in Fig. 7. The test sequence of shear-displacement cycles was similar to that for the long-joint test.

Of the four specimens tested, two were fabricated with no vertical tie through the joint. The other two had a central steel bar acting as a vertical tie. Specimens were marked R1 to R4.

Specimen R1 - No vertical tie was provided in Specimen R1. A wall load of 700 psi (4.83 MPa) was maintained during testing.

Specimen R2 - A vertical tie with a coupler joining the upper and lower bars was centered in the joint of Specimen R2 as shown in Fig. 8. A sheet rubber padding 1/8-in. (3 mm) thick was placed on the tie. The padding covered the coupling element and the space around the rod for a length of 6 in. (152 mm) above and below the coupler. A wall load of 700 psi (4.83 MPa) was maintained during cyclic loading.

Specimen R3 - Specimen R3 was similar to Specimen R1. The standard sequence of load cycles with a wall load of 700 psi (4.83 MPa) was augmented with additional load cycles at several different wall loadings.

Specimen R4 - A vertical tie was centered in the joint of Specimen R4. This tie was not padded. A wall load of 700 psi (4.83 MPa) was maintained during shear-displacement cyclic loading.

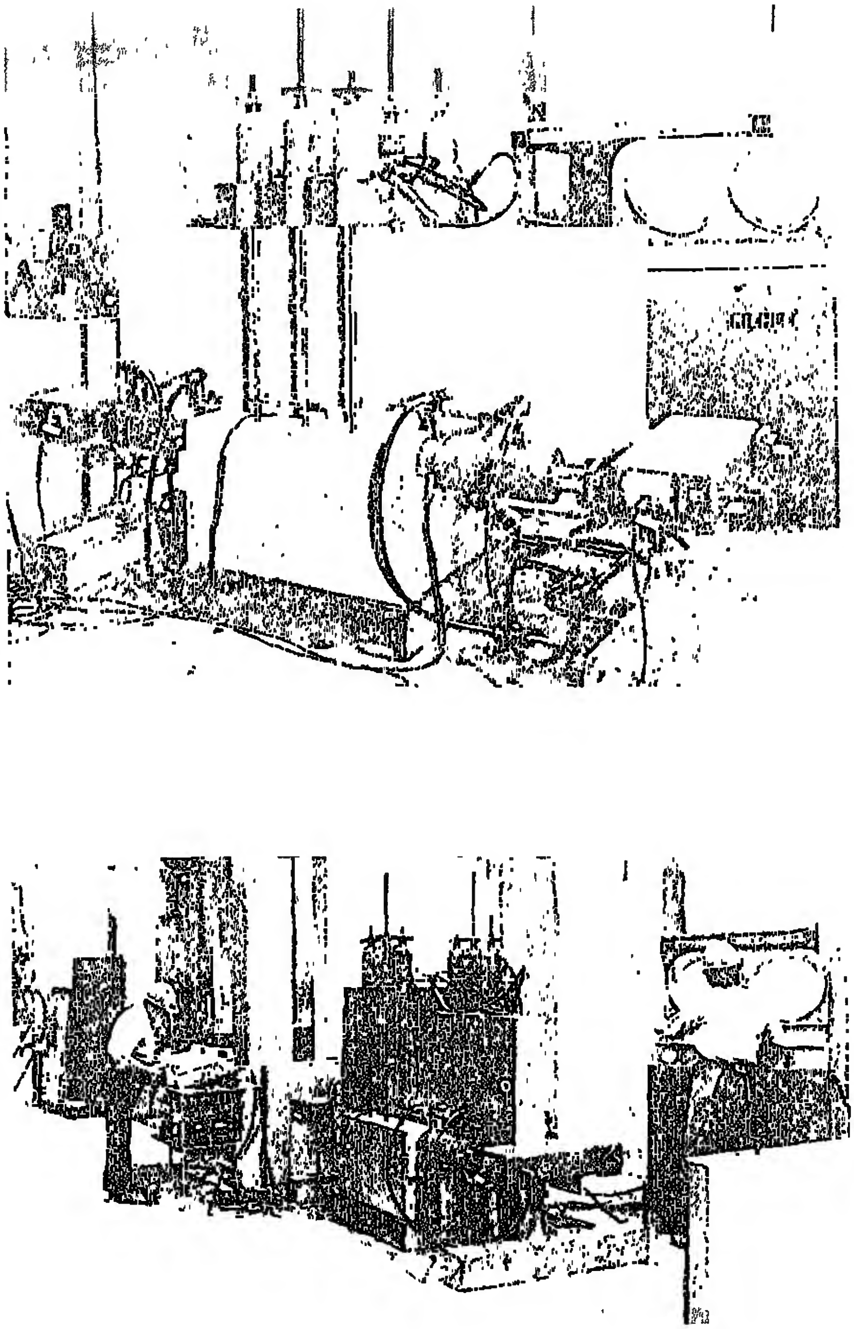


Fig. 7 Test Setup for Short-Joint Specimens

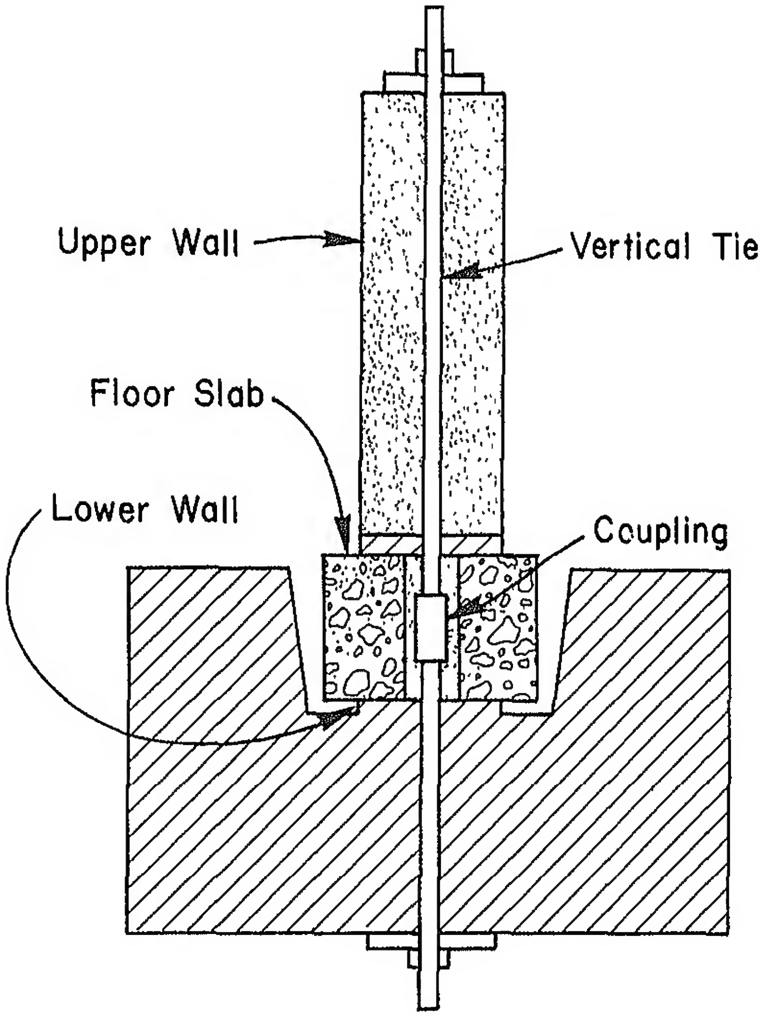


Fig. 8 Vertical Tie in Short-Joint Specimen

3. TEST RESULTS

3.1 Long-Joint Specimen

Repeated reversals of shear loading to predetermined slip values were applied to the specimen. A plot of shear versus displacement is shown in Fig. 9 for the 17 loading cycles. The data presented in Table 1 show the specific points in each loading cycle as identified in Fig. 10.

A constant normal force of 264 kips (1174 kN) was applied to the wall. Initial peak shear force of 107 kips (476 kN) was divided by the normal force to obtain a friction coefficient of 0.405. For Cycles 2 through 17, the average sliding force was calculated as the average shear force at zero displacement (Columns B and E in Table 1). This average value of 45.5 kips (202 kN) was then divided by the normal force to result in an average friction coefficient of 0.17.

Within the joint, the plane of sliding was located between the top of the drypack and the underside of the upper wall. Figure 11 shows the sliding surface after wall removal at the end of the test. A smooth undamaged surface at the top of the drypack grout was evident. The mating surface of the lower edge of the wall also had a smooth and polished finish. The cracking evident in the figure occurred at initial slip of the joint. Bond strength at the interface reached an average stress of 280 psi (1.93 MPa) before initial slip. Sudden release and sliding caused the crack at the end of the floor slab. This cracking did not interfere with the test.

The test demonstrated an energy-absorbing system with no visible deterioration. Area inside the loop at each cycle is a measure of energy absorbed. Rectangular shape of the loops is very good for seismic resistance. A low value for the coefficient of friction is surprising. It seems to be a function of the smoothness of the interface and the method of manufacture.

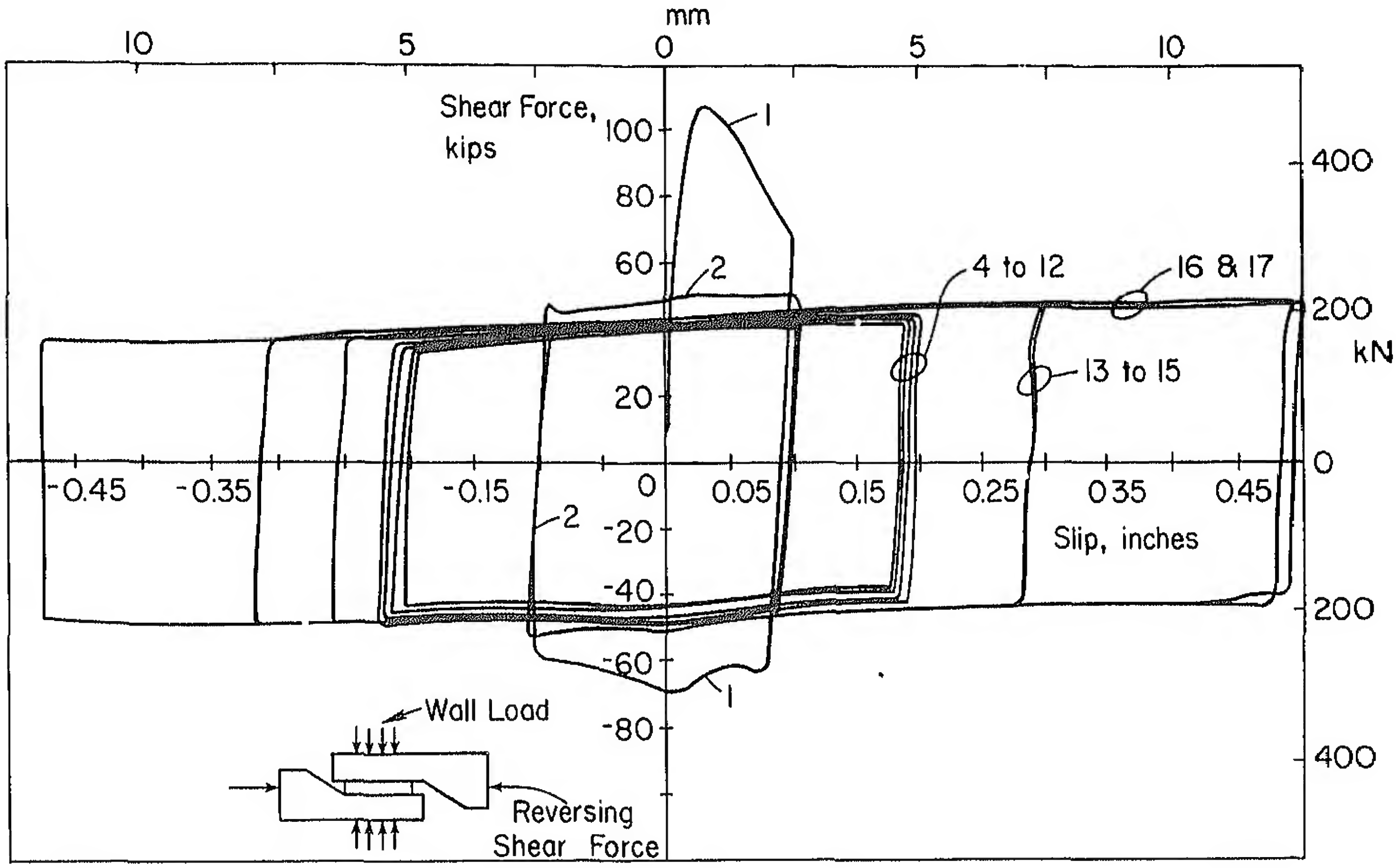


Fig. 9 Shear Displacement Cycles From Long-Joint Specimen

TABLE 1 - TEST RESULTS FOR LONG-JOINT SPECIMEN

Load Cycle	Shear Force at Points Indicated in Fig. 10, kips						Maximum Slip in.	
	A	B	C	D	E	F	Right	Left
1	107	-	67	64	70	60	0.10	0.10
2	44	49	52	48	51	53	0.11	0.11
3	43	44	47	43	44	47	0.10	0.10
4	41	41	47	46	45	47	0.21	0.20
5	39	42	44	40	44	44	0.21	0.19
6	37	42	46	41	42	43	0.21	0.20
7	37	42	46	40	44	44	0.21	0.21
8	38	45	50	41	46	46	0.21	0.21
9	40	45	49	42	46	46	0.20	0.22
10	38	44	50	42	47	48	0.21	0.23
11	40	46	48	42	47	46	0.20	0.21
12	40	46	48	42	47	46	0.20	0.21
13	39	44	49	44	48	48	0.30	0.31
14	39	46	50	41	48	47	0.30	0.31
15	39	47	50	42	48	47	0.30	0.31
16	39	46	51	45	49	48	0.50	0.48
17	39	46	51	42	48	47	0.49	0.48

Note: 1 kip = 4.448 kN, 1 inch = 25.4 mm

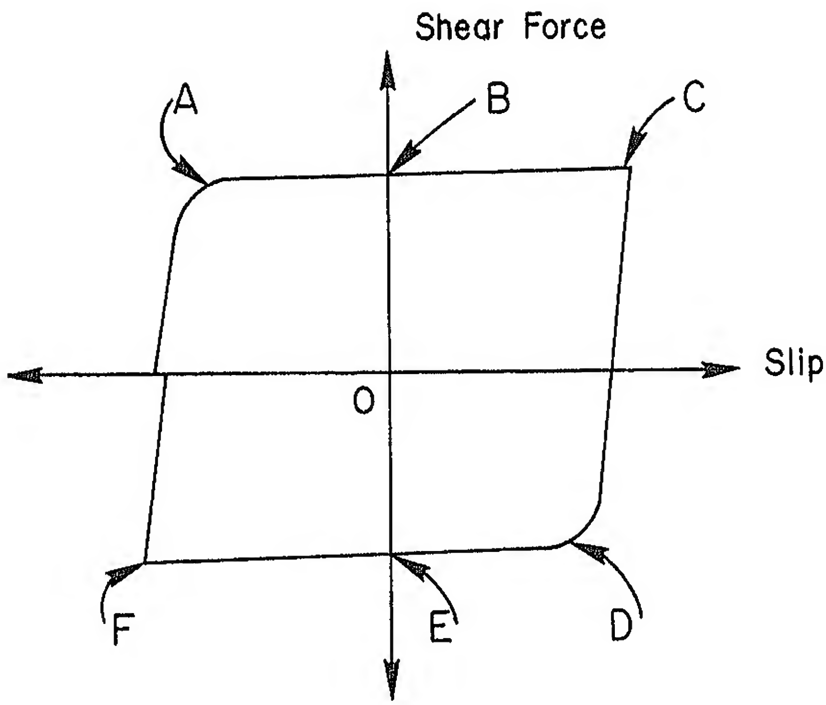


Fig. 10 Location of Data Points

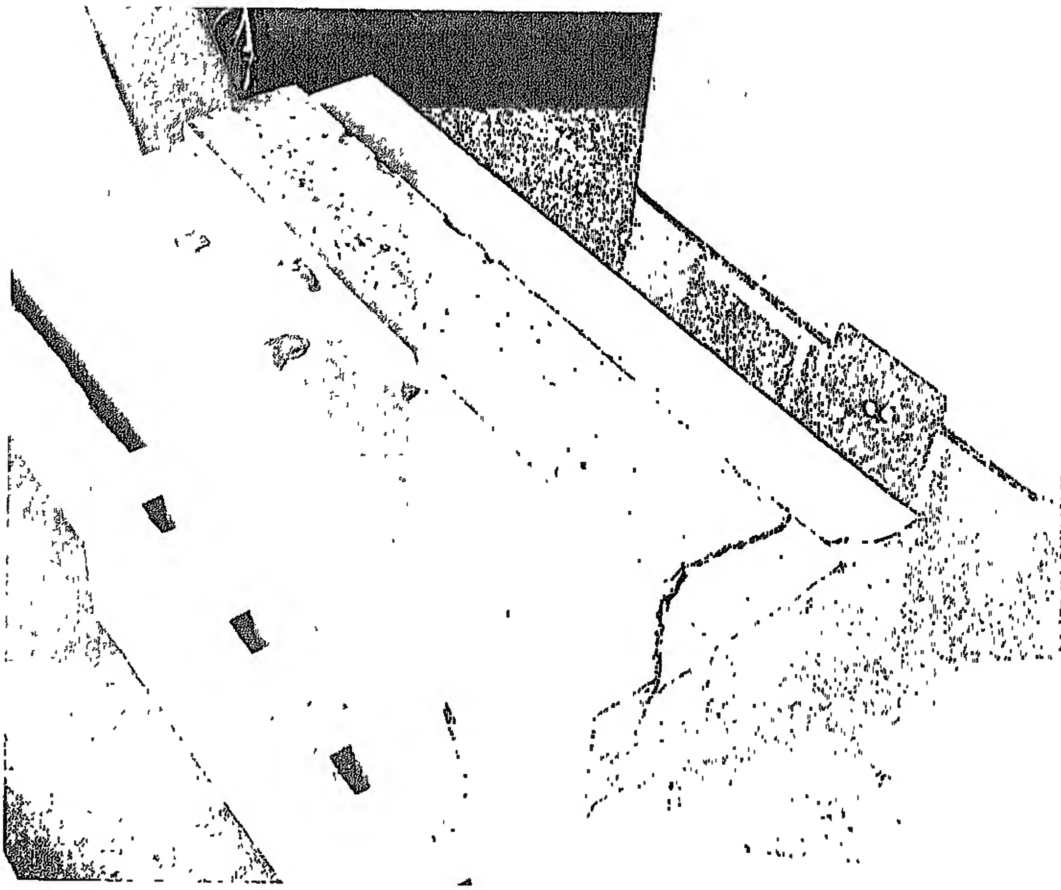


Fig. 11 Long-Joint After Test

3.2 Short-Joint Specimens

Repeated reversals of shear loading to predetermined slip values were applied to the four specimens with the 2-ft (610 mm) long-joint. A plot of shear versus displacement for each specimen is shown in Fig. 12.

Specimen R-1 - A listing of data is presented in Table 2 for the specific points on each loading cycle as identified in Fig. 10. The normal force on the wall was 134 kips (596 kN). The initial peak force of 120 kips (534 kn), corresponds to a friction coefficient of 0.9. An average sliding force of 59.9 kips (266 kN) converts to a friction coefficient of 0.45.

For this joint the sliding plane was between the top of the lower wall and the grout in the joint's core. This interface is illustrated in the photograph in Fig. 13. In the foreground is the top of the lower wall section while the floor portion is rotated to show the underside. The crack in the lower wall section resulted when the specimen was disassembled for inspection. A crack in the grout, between the concrete pieces representing the floor slabs, occurred at initial slip. Bond strength at the interface reached an average stress of about 1250 psi (8.62 MPa) for the reduced width of bonded surface.

Sudden slip at the left edge in the picture in Fig. 13 caused a crack in the grout and slip of the grout column between the two slab ends. Another detail visible in this picture is the line indicating the edge of the plastic bearing pads. In Fig. 3 these bearing pads are shown with their inner edges in line with the inner ends of the floor slabs. For Specimen R1, the pads were mistakenly lined up with the outside edge of the lower wall. The space under the floor slab, therefore, was filled with grout up to the bearing pad. Consequently, the major portion of wall load had a 4-in-wide (102 mm) grout column rather than the intended 3-in-wide (76 mm) grout column through the joint. It cannot be ascertained if this change or the crack in the grout had a major effect on the coefficient of friction.

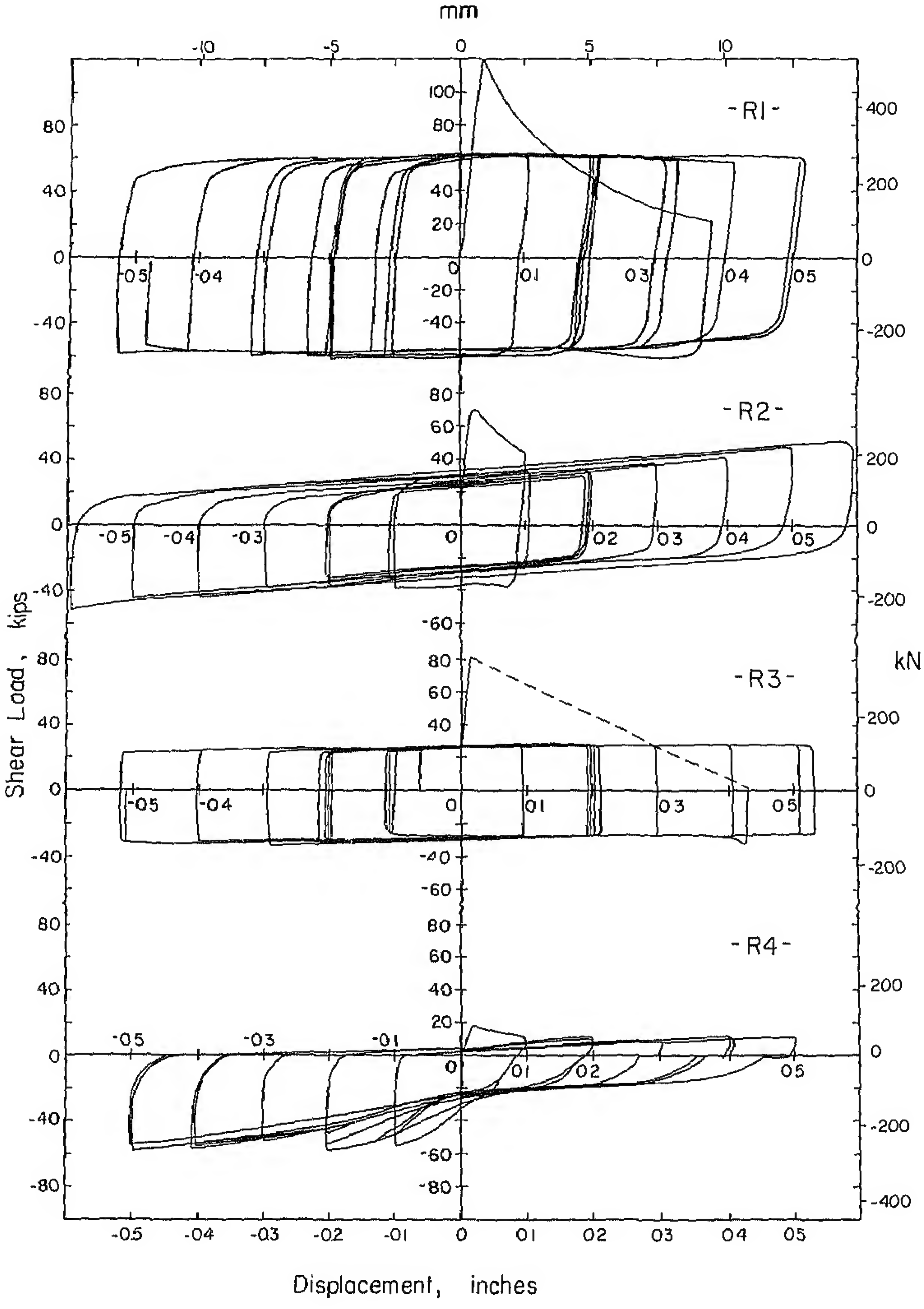


Fig. 12 Shear Displacement Cycles from Short-Joint Tests

TABLE 2 - TEST RESULTS - SPECIMEN R1

Load Cycle	Shear Force at Points Indicated in Fig. 10, kips						Maximum Slip in.	
	A	B	C	D	E	F	Right	Left
1	120	-	22	59	59	57	0.37	0.13
2	52	57	59	56	58	58	0.11	0.11
3	53	59	62	56	58	60	0.11	0.10
4	56	59	60	56	60	60	0.21	0.21
5	56	60	63	55	60	62	0.20	0.20
6	56	60	63	55	60	61	0.20	0.20
7	56	60	62	55	60	61	0.20	0.20
8	56	60	62	55	60	61	0.20	0.20
9	56	61	62	54	60	60	0.20	0.24
10	55	61	62	54	60	60	0.20	0.20
11	55	61	62	54	60	60	0.20	0.21
12	55	61	62	54	60	60	0.20	0.20
13	56	61	60	52	60	59	0.31	0.32
14	58	61	58	52	60	58	0.33	0.30
15	60	61	59	57	59	57	0.41	0.42
16	51	61	61	53	59	59	0.51	0.53
17	51	61	61	53	59	57	0.52	0.48

Note: 1 kip = 4.448 kN, 1 inch = 25.4 mm

Fig. 13 Sliding Interface for Specimen R1

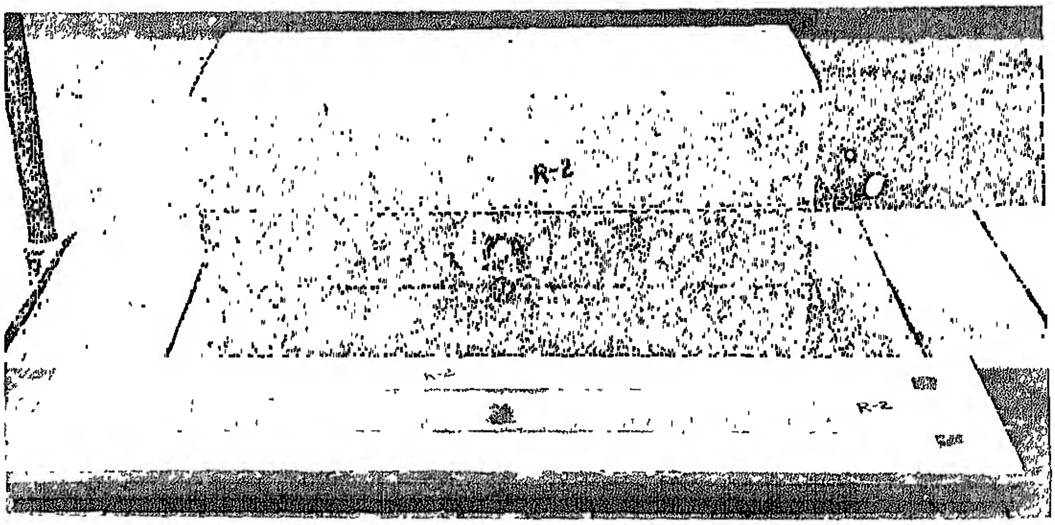


Fig. 14 Sliding Interface for Specimen R2

The contact surface was damaged only slightly by the 17 cycles of sliding. Portions of the top surface of the wall part were smooth and polished similar to that noted in Specimen S1.

Fig. 12 shows that the cyclic curves for Specimen R1 are nearly rectangular in shape. For each new application of load there was a slight rounding of the shear-displacement curve at the corners instead of the square shape noted for the previous specimen. The higher value for the coefficient of friction for Specimen R1 is at the value expected from the literature study.

Specimen R2 - A padded vertical tie was centered in the joint length of Specimen R2. The plot of the cyclic test is shown in Fig. 12 and listing of specific data points is given in Table 3. Normal force on the wall was 134 kips (596 kN). An initial peak force of 72 kips (320 kN) corresponds to a friction coefficient of 0.54, the average shear force of 26.8 kips (119 kN) converts to a coefficient of 0.20.

In the joint of Specimen R2 the plane of sliding was also at the top of the lower wall. This interface is shown in Fig. 14. The vertical tie was cut with a torch to gain access to the slip plane. The clean edge of the grout column is evident in the photograph. Bearing pads in Specimen R2 were positioned to the inner edge of the floor slab ends. Although hardly noticeable, there is a visible crack in the grout column at approximately the same location as noted previously in Specimen R1. The matching faces show an extremely smooth and polished surface except immediately around the vertical tie. Concrete was pulverized in the lower wall at the two sides of the tie due to interference from slip movements. This location is shown in further detail in Fig. 15. Movement of material caused a rounding of the original sharp corner to permit the vertical tie to repeatedly accommodate the large displacements without damage. The positive slope of the load line during sliding on each cycle indicates the additional resistance due to tie bending and concrete bearing the vertical tie. In Cycle 15, for example, the shear force variation is almost linear. The magnitude of this variation was 26 kips (116 kN) over a total movement of 0.8 in.(20.3 mm), or 32.5 kips per inch (5.71 MN/m).

TABLE 3 - TEST RESULTS - SPECIMEN R2

Load Cycle	Shear Force at Points Indicated in Fig. 10, kips						Maximum Slip in.	
	A	B	C	D	E	F	Right	Left
1	72	-	44	37	38	38	0.10	0.10
2	24	31	35	24	29	34	0.11	0.10
3	20	27	31	24	28	33	0.10	0.11
4	18	24	33	20	28	37	0.20	0.20
5	16	26	32	20	28	34	0.20	0.20
6	16	24	32	18	26	32	0.20	0.20
7	16	24	32	18	26	32	0.20	0.21
8	16	24	31	18	26	32	0.20	0.20
9	16	24	32	20	26	33	0.20	0.21
10	16	24	32	20	26	33	0.19	0.21
11	16	24	32	20	26	33	0.19	0.21
12	16	24	32	20	26	33	0.20	0.21
13	16	24	36	18	26	38	0.30	0.30
14	16	25	41	16	30	44	0.40	0.40
15	15	27	41	16	30	42	0.40	0.40
16	16	25	45	17	29	49	0.50	0.50
17	12	27	46	18	33	49	0.50	0.50
18	12	27	48	18	36	56	0.60	0.60

Note: 1 kip = 4.448 kN, 1 inch = 25.4 mm

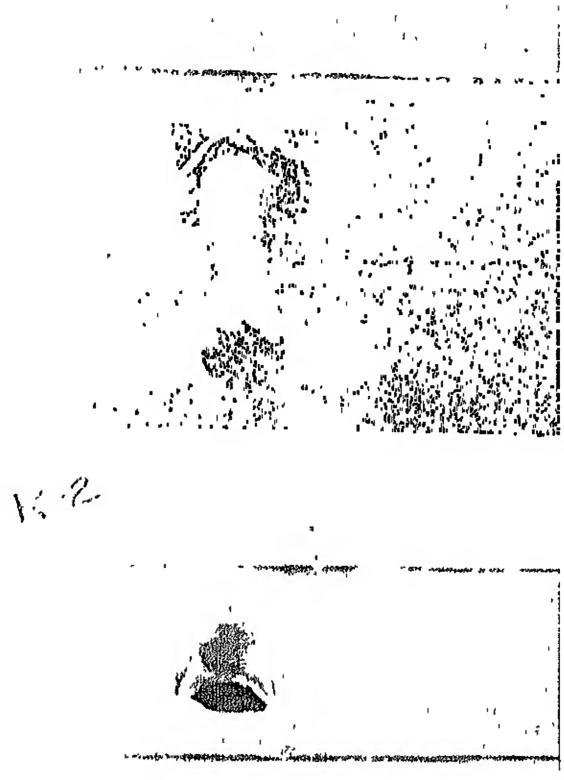


Fig 15 Details at Vertical Tie - R2

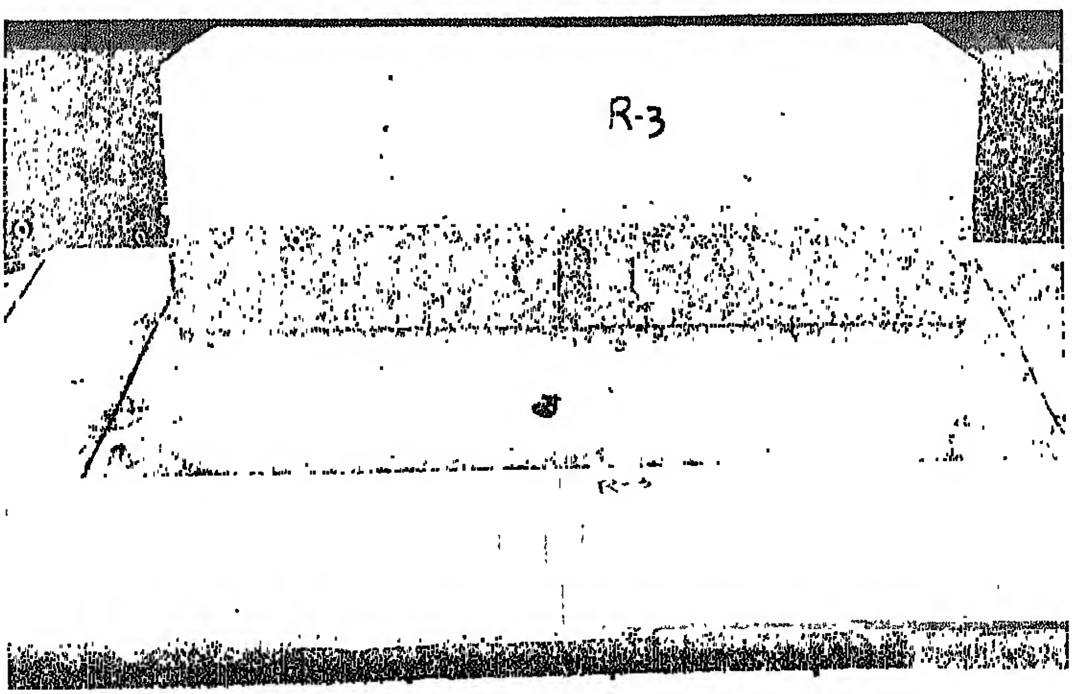


Fig. 16 Sliding Interface - Specimen R3

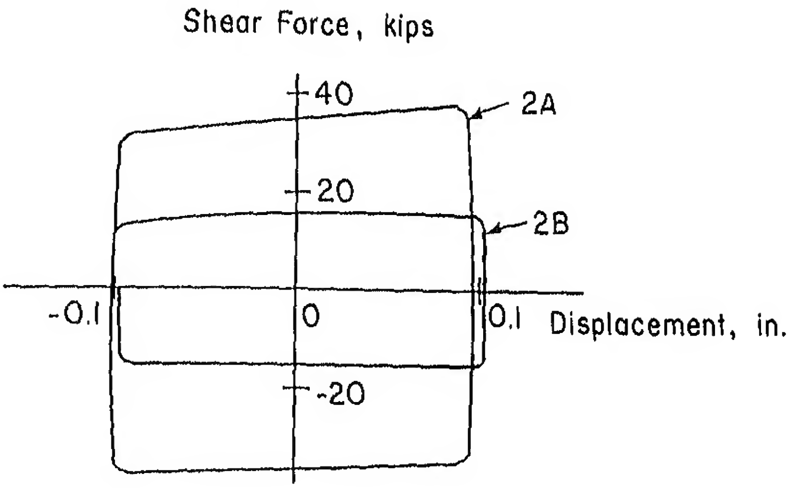
Specimen R3 - Specimen R3 was similar to R1 but was built with the plastic pads in the intended location. Vertical load on the wall was varied to determine the effect of normal force on coefficient of friction. The main sequence of cyclic loading is similar to that shown in Fig. 12. As in previous specimens, the normal force on the wall for the main sequence was 134 kips (596 kN) or 700 psi (4.83 MPa). Extra load cycles are shown in Fig. 17. The two cycles marked (a) were conducted at high and low loads, just after Cycle 2 in the main sequence. Normal force was 50% above and below the normal force used in the main sequence. The three cycles marked (b) were conducted after Cycle 17. The normal force for these cycles was 25%, 50% and 125% of the main sequence value.

A listing of data is presented in Tables 4 and 5. The initial peak force of 82 kips (365 kN) corresponds to a coefficient of friction equal to 0.61. The average shear force for the main sequence of cycles was 29 kips (116 kN) which converts to a coefficient of friction equal to 0.22.

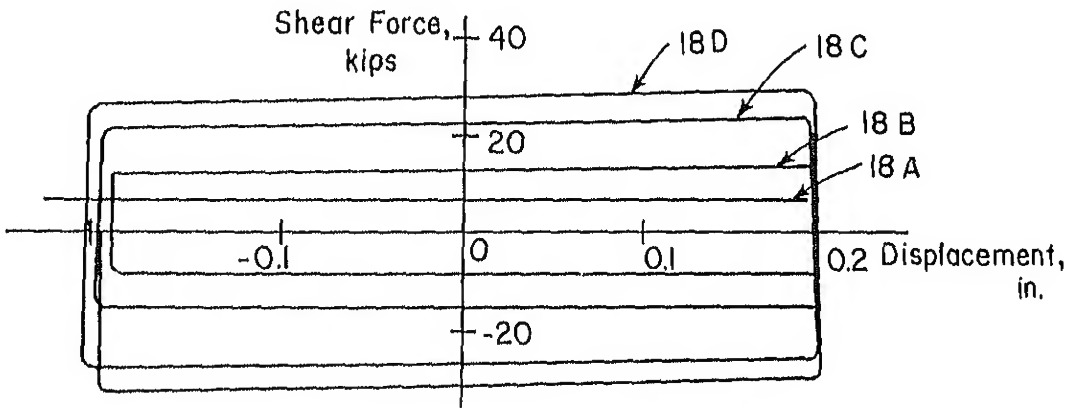
The normal force on the wall was varied to produce wall stress from 175 psi to 1050 psi (1.21 to 7.24 MPa). Measured coefficients of friction were 0.24, 0.22, 0.17, 0.18 for wall stresses of 175, 350, 875 and 1050 psi (1.21, 2.41, 6.03 and 7.24 MPa) respectively.

The plane of sliding in Specimen R3 was at the top of the lower wall. This interface is shown in Fig. 16. Again, there is a vertical crack visible in the grout column at about the same location as noted in Specimens R1 and R2. There is no evidence to indicate that the crack influenced the test results. Matching surfaces exhibited an extremely smooth and polished surface. The very rectangular nature of the repeated cycles, with retracing of lines, indicates minimum change or damage with repeated cyclic loading.

Specimen R4 - Specimen R4 was similar to R2 but the vertical tie was not padded. The effect of the tie was obvious on the first loading cycle. Direct bearing of the grout on the tie at the sliding surface is indicated in Fig. 18. Sudden release of energy, due to destruction of bond between mating surfaces, resulted in a sudden displacement. In this case, besides local crushing of the grout bearing on the tie, the grout



(a) After Cycle 2



(b) After Cycle 17

Fig. 17 Extra Load Cycles - Specimen R3

TABLE 4 TEST RESULTS - SPECIMEN R3 - MAIN SEQUENCE

Load Cycle	Shear Force at Points Indicated in Fig. 10, kips						Maximum Slip in.	
	A	B	C	D	E	F	Right	Left
1	82	-	2	32	29	27	0.43	0.11
2	25	27	29	27	28	27	0.10	0.10
3	24	27	28	27	28	29	0.10	0.10
4	25	28	28	28	28	29	0.20	0.20
5	25	28	28	28	31	32	0.20	0.20
6	25	28	28	28	31	32	0.20	0.21
7	25	28	28	28	31	32	0.20	0.20
8	25	28	28	28	31	32	0.20	0.21
9	26	28	28	29	30	31	0.20	0.20
10	26	28	28	29	30	31	0.20	0.20
11	26	28	28	29	30	31	0.21	0.20
12	26	28	28	29	30	31	0.20	0.20
13	24	28	28	28	30	34	0.30	0.29
14	24	28	29	27	31	32	0.41	0.40
15	22	28	29	27	31	32	0.40	0.40
16	29	28	29	26	31	32	0.51	0.52
17	28	28	28	26	31	32	0.53	0.51

Note: 1 kip = 4.448 kN, 1 inch = 25.4 mm

TABLE 5 TEST RESULTS - SPECIMEN R3 - EXTRA CYCLES

Load Cycle	Shear Force at Points Indicated in Fig. 10, kips						Maximum Slip in.		Wall Stress Psi
	A	B	C	D	E	F	Right	Left	
2A	33	36	39	36	37	39	0.10	0.10	1050
2B	13	15	16	16	16	16	0.10	0.10	350
18A	7	7	7	8	9	9	0.20	0.19	175
18B	12	13	13	15	16	16	0.20	0.19	350
18C	22	23	24	26	27	28	0.20	0.19	700
18D	27	28	30	30	32	35	0.20	0.20	875

Note: 1 kip = 4.448 kN, 1 inch = 25.4 mm, 1 psi = 6.895 kPa

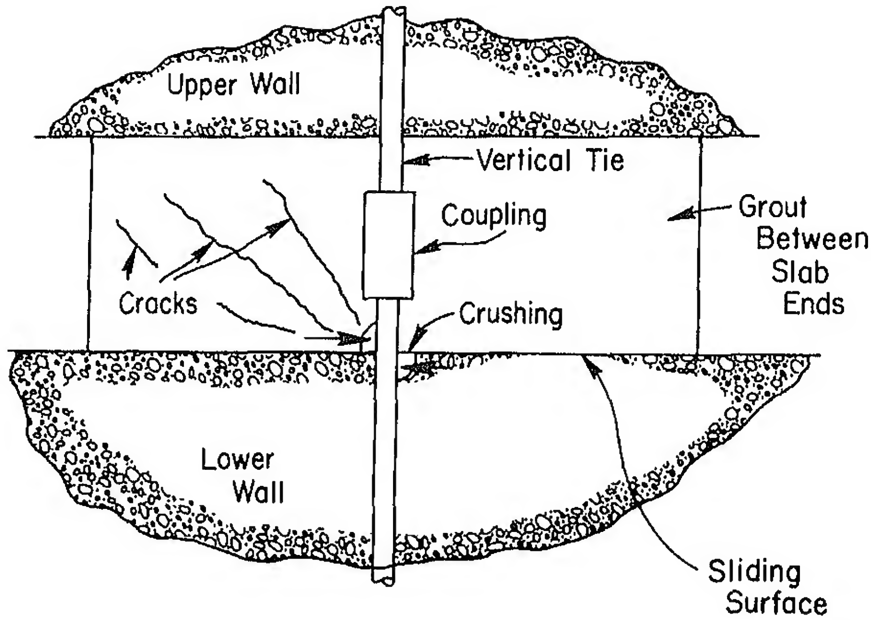


Fig. 18 Grout Cracking

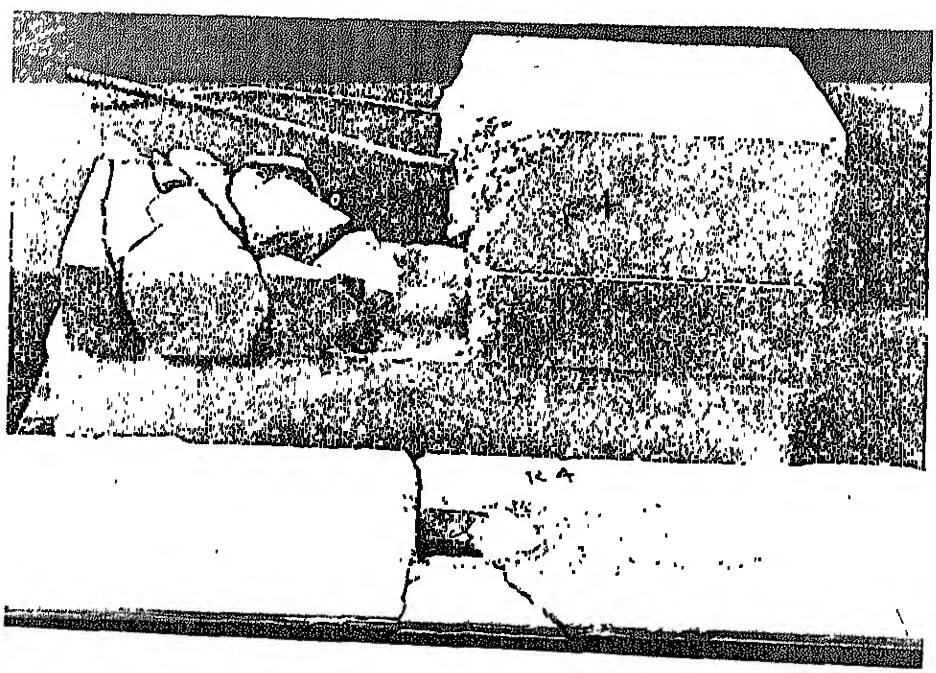


Fig. 19 Specimen R4 After Test

was cracked and split between the slab ends. The latter phenomenon is indicated in the diagram in Fig. 18 and pictorially shown in Fig. 19. The photograph of the specimen disassembled after testing shows the split grout on one side of the vertical tie. The slab part on the left side was cut away to expose the grout damage. Cracking in the lower wall piece in the foreground resulted from disassembly and not from the test.

Loss of integrity of the grout on the left side disturbed the top half of each loading cycle that appears above the line in Fig. 12. The part of each cycle below the line indicates several phenomena. Due to the floor slab sliding to the left (below the line in Fig. 12) there was a major increase in force due to interference between the grout and vertical tie. Crushing of the grout reduced the height of the load peak for each successive cycle at the same displacement. The curve at the unloading part indicates a considerable restoring force. This may be due to the extra freedom for tie-bending that is allowed by the considerable cracking of the grout.

Severe damage in Specimen R4 indicates the potential for damage of a large vertical tie as it passes through a narrow grout column of a joint subject to sliding motions. Padding of the tie as in Specimen R2 would eliminate this damage.

4. CONCLUSIONS

The initial peak load for bond slip is extremely variable. Since construction and temperature induced movements will probably cause prior slippage at the joints in a LP building, the initial peak is of no meaning towards seismic resistance.

Values for coefficients of friction for the extremely smooth surfaces used in tests described in the report were lower than the values reported previously. Data from these tests are shown in Fig. 20 along with those from other sources. Normal stress used for the plot of the new values is the normal force divided by the grout area at the sliding surface. Grout width for the long-joint specimen at the slip plane was 8 in. (203 mm). Width for Specimen R1 was 4 in. (102 mm), while that for R2 and R3 was 3 in. (76 mm). In the above calculation of normal stress, it is assumed that 100% of the wall load is transferred through the grout column. Tests reported in Supplemental Report B[6] indicate that up to 10% of the wall load is transferred through the plastic bearing pads adjacent to the grout column for the level of wall load used in these specimens. A recalculation of normal stress using 90% of the vertical load on the grout column would move the lowest group of data points in Fig. 20 to the left by 10%. However, the friction coefficient would remain the same.

With the exception of Specimen R1, coefficient of friction values from these new tests are about one-half the previous values. The sliding surface of Specimen R1 was not as smooth and polished in appearance after the test as the other specimens. These tests indicated that the coefficient of friction for smooth surfaces is from 0.2 to 0.4 with the lower values associated with extreme smoothness. Also, smooth surfaces offer repeatable sliding without severe damage.

Protection of the joint from damage at a vertical tie requires padding of the tie. Thin sheet rubber wrapping on a vertical tie reduced local damage in one specimen as compared to severe damage in one specimen without padding.

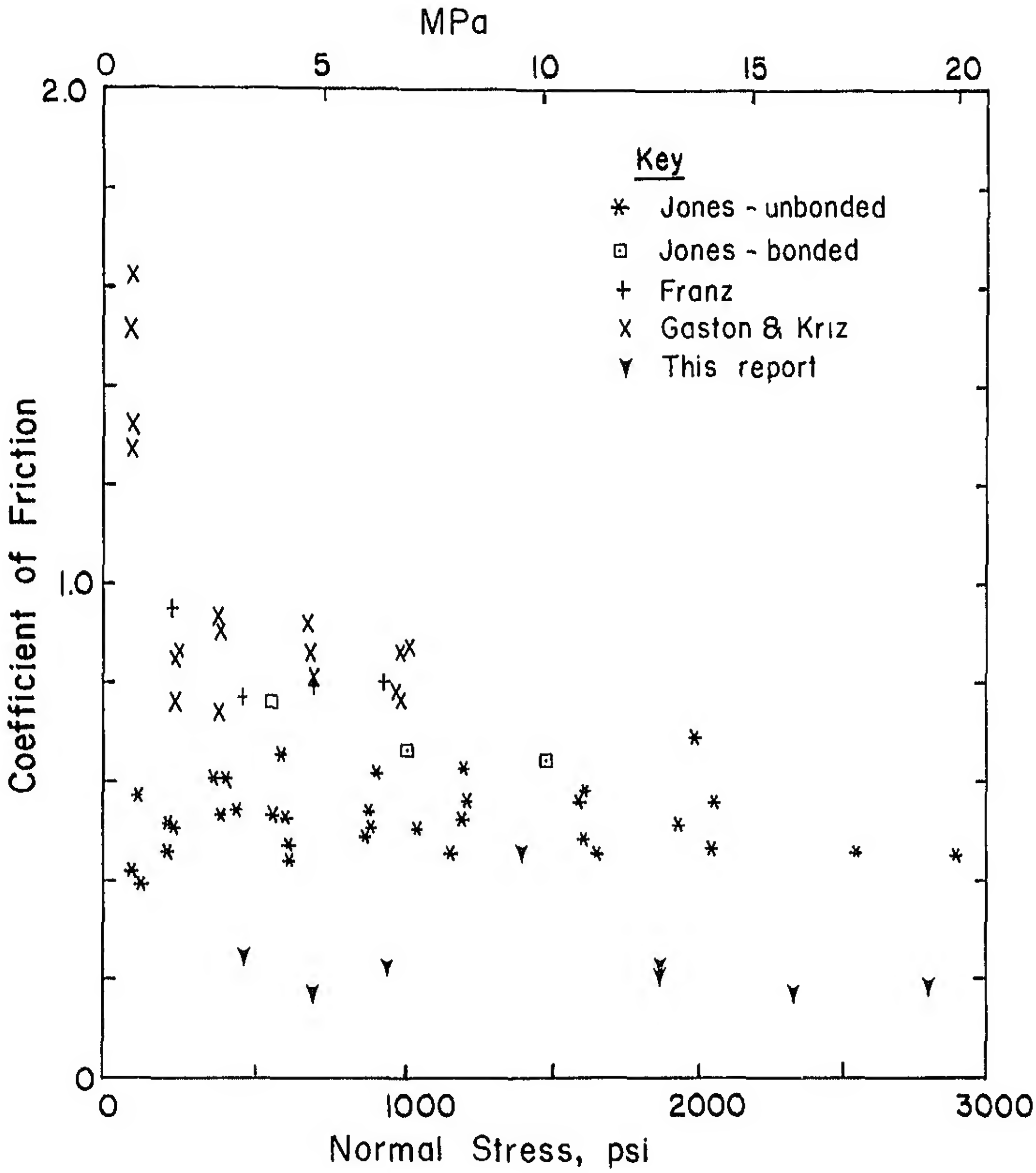


Fig. 20 Coefficient of Friction

The near rectangular shape of a cycle of load versus displacement is altered to a parallelogram by the padded vertical tie. This is shown in Fig. 21. Slope of the topline of the parallelogram was 32.5 kips (145 kN) of force for each inch (25 mm) of displacement for a 1-in. diameter (25 mm) tie crossing the joint.

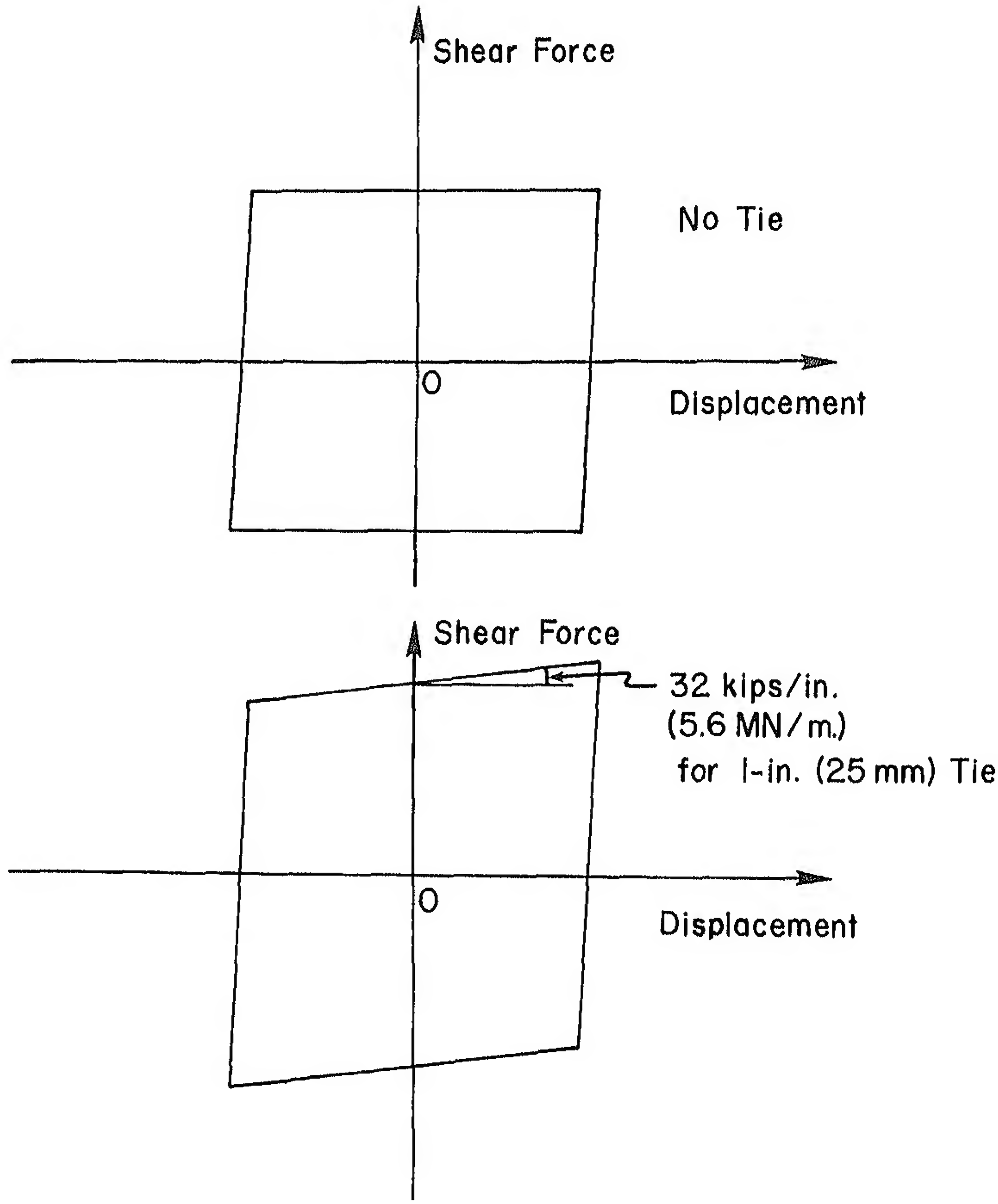


Fig. 21 Shape of Shear-Displacement Diagrams

APPENDIX A - GLOSSARY OF TERMS

Connection:	A position or region where two or more building components, panels or assemblies are put together or united.
Cross-wall system:	A large panel system in which the load-bearing walls are perpendicular to the longitudinal axis of the building
Deformation:	A change in dimension or shape due to stress.
Dowel:	A steel bar which extends into two adjoining portions of a concrete construction.
Dowel action:	Shear force applied in the plane of the cross section of a dowel.
Dry pack:	To forcibly ram a moist portland cement and aggregate mixture into a confined area; also, the mixture so placed.
Dry-packed concrete:	A concrete mixture sufficiently dry to be consolidated by heavy ramming.
Floor panel:	A horizontal precast concrete element reinforced with mild or high-strength steel.
Friction coefficient:	The ratio of the force required to slide a body along a plane to the normal force is called the friction coefficient.

General Structural Integrity: (GSI)	The ability of a structure to transfer loads from one portion or element which has lost its load-bearing capacity to the surrounding elements to inhibit progressive collapse while retaining structural stability; achieved through a degree of continuity conbined with a degree of ductility of the components and connections of a structure.
Grout:	Mixture of cementitious material and aggregate to which sufficient water is added to produce pouring consistency without segregation of the constituents.
Grouting:	The process of filling with grout.
Horizontal joint:	The zone common to the wall and floor panels in a horizontal direction.
Large panel structure:	A structural system composed of vertical load-carrying elements of large precast wall panels with precast floors and roofs of panels or planks.
Normal force:	A force at 90^{0} to and causing a compression stress on a slip plane.
Seismic loading:	Force or displacement imposed on a structure in response to earthquake ground motion.
Spine-wall system:	A large panel system in which the load-bearing walls are parallel to the longitudinal axis of the building.
Vertical tie:	The tie used to vertically link adjacent lifts of wall elements in the same plane.

APPENDIX B - DETAILS OF EXPERIMENTAL PROGRAM

B.1 Manufacture and Assembly of Specimens

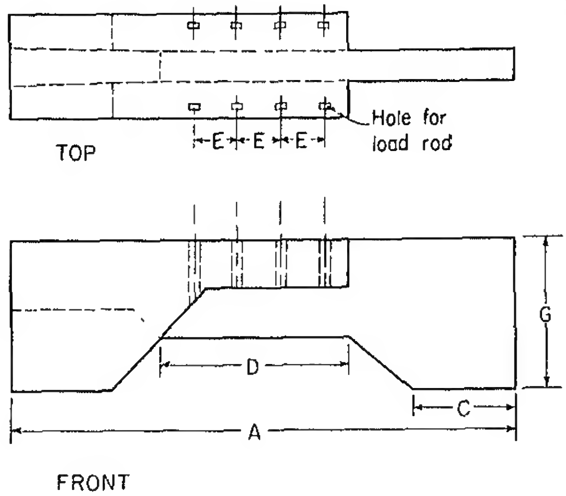
Each specimen was an assembly of three precast parts consisting of lower wall, slab and upper wall. These were grouted together to make joint specimens.

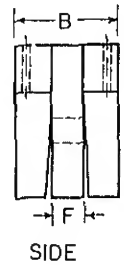
Long-Joint Specimen - Wall dimensions and reinforcement details are shown in Fig. 22. The lower wall part was cast with the surface marked "top of wall," in Fig. 22, at the bottom of the form. This insured a smooth surface of concrete as cast against a plastic coated plywood form. The upper wall part also was cast in the same orientation so the bottom of the wall was downward. The cast parts were covered and left in the form for 7 days of curing before removal.

Dimensions and reinforcement for the precast slab are shown in Fig. 23. The central void space was formed by foam plastic which was removed later. The slab part was covered to cure in the form for 7 days prior to removal.

The specimen was assembled as a typical building joint as shown in Fig. 3. The lower wall part was rotated 180° to place the top of the wall upward. Plastic bearing pads were placed to support the floor slab part. Grout was poured to fill the central void between slab ends. One day later the upper wall part was positioned and supported to leave room for the dry pack. After packing the 1-in. (25mm) thick drypack, the specimen was left to cure for 7 days.

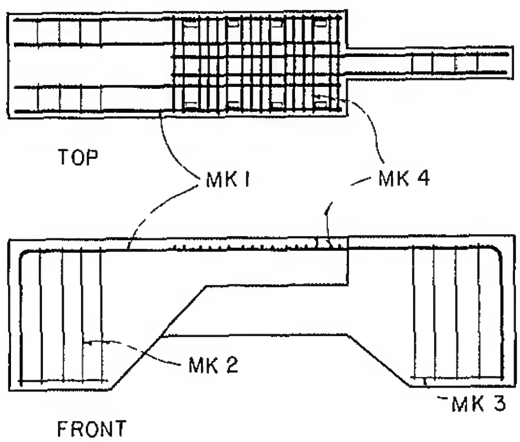
Prior to upending the specimen to the test position shown in Fig. 6, wall loading was applied to hold the pieces together. Steel rods with end washers and nuts were inserted through the eight holes in each wall part. Each rod also passed through the center hole of a 30-ton (267 kN) hydraulic ram[6] on one end as seen in Fig. 6. Pressure was increased in a single hydraulic system connected to the eight rams to apply the desired wall loading. This load was maintained constant as the specimen was turned to the test position and moved into place.

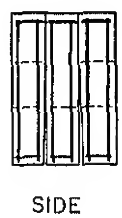




DIMENSIONS

	inches	mm
A	140	3560
B	27	699
C	28	711
D	56	1422
E	12	305
F	8	203
G	40	1016

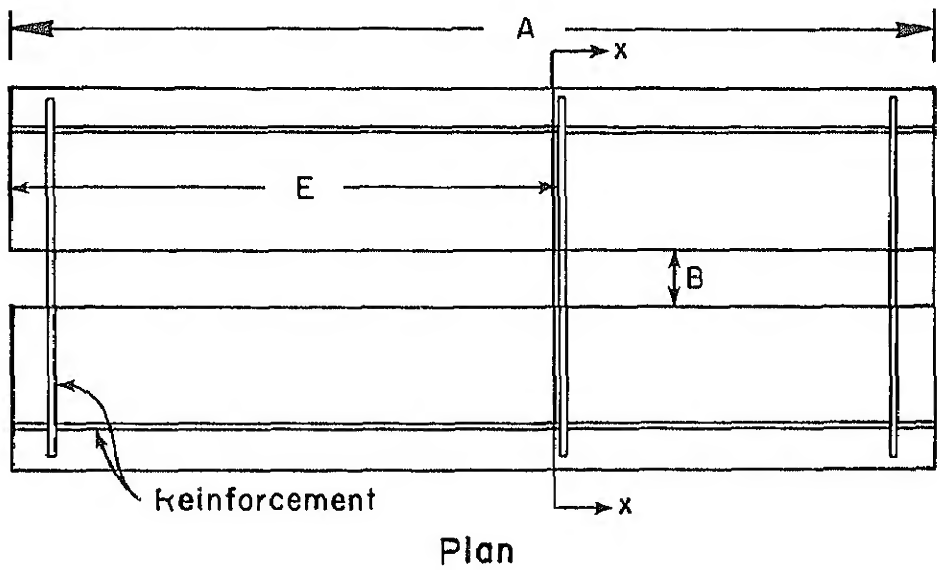


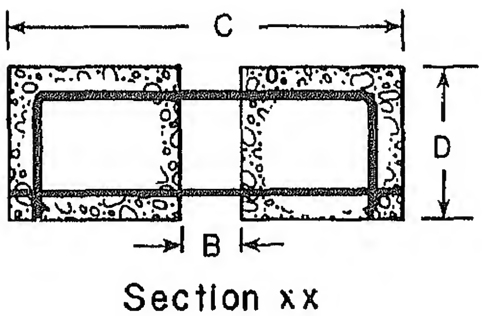


REINFORCMENT

MK	DIAMETER inches	mm
1	1	25
2	3/8	9.5
3	3/8	9.5
4	3/4	19

Fig. 22 Dimensions and Reinforcement - Wall Segment for Long-Joint Specimen





Note – All Reinforcement 3/8 - in. (9.5 mm)

Dimensions

	Inches	mm
A	48	1219
B	3	76
C	20	508
D	8	203
E	26	660

Fig. 23 Slab Part for Long-Joint

upper- and lower-test brackets are shown in Fig. 24. Insert pieces were precast and attached to these brackets to complete the lower wall and upper wall parts. Replaceable inserts are shown in Fig. 25. The surfaces marked "smooth" were cast downward against plastic-coated plywood forms. The rough surfaces were formed against textured rubber matting. Cast inserts, upper and lower brackets were covered and left in the form for 7 days of curing before removal.

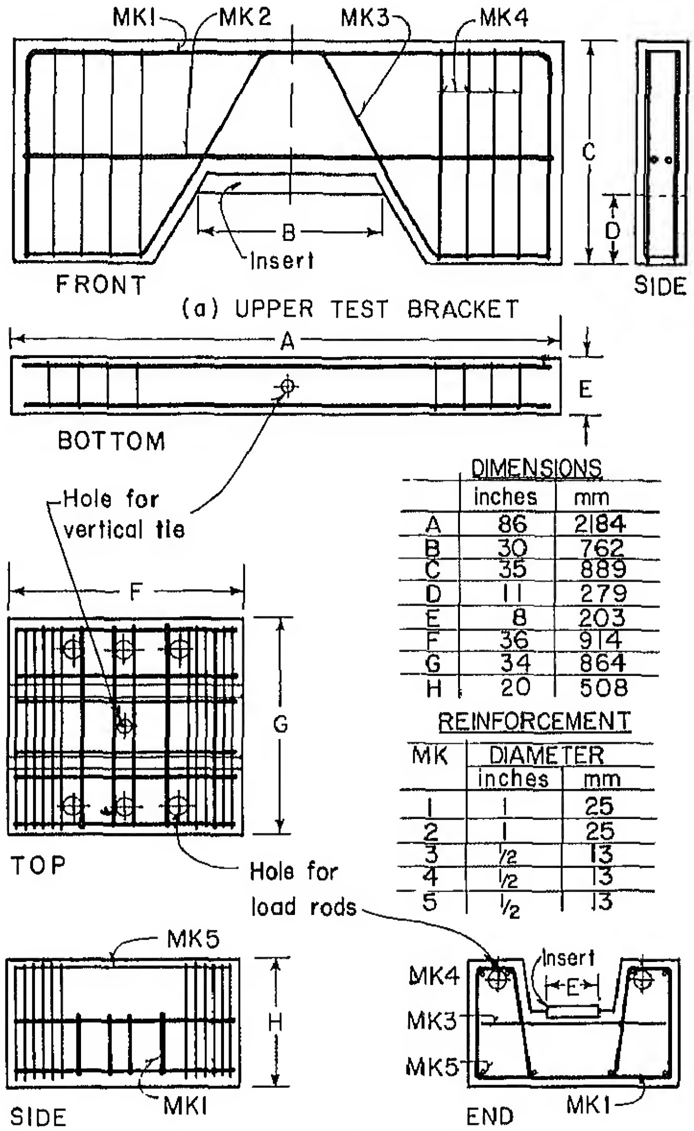
Dimensions and reinforcement for the precast slab are shown in Fig. 26. The central void space was formed by foam plastic which was removed later. The slab part was covered and left in the form for 7 days of curing before removal.

Each specimen was assembled to represent the typical building joint as shown in Fig. 3. The lower wall insert was secured to the lower test bracket with high-strength plaster between the rough surfaces. Two 1/2-in.-diameter (12.7 mm) bolts fastened each end of the insert to the bracket. Plastic bearing pads were placed to support the floor slab part. Grout was poured to fill the central void between slab ends. One day later, the upper wall insert was positioned and fixed to leave room for accommodating the drypack. After packing the one-inch thick drypack, the material was left to harden one day prior to installing the upper bracket. High-strength plaster was placed on the rough top surface of the upper wall insert to mate with the rough surface of the upper bracket.

Vertical ties were used in two specimens. These were installed and grouted through precast holes in the brackets and inserts. A washer on each exposed end was held in place by a nut on the threaded rod end. The nut was turned to an initial snug-fit condition between the nut and washer. Wrench tightening was not used.

Edges of the drypack grout were covered and cured for 7 days.

Prior to testing, hydraulic loading equipment and load rods were assembled as shown in Figs. 7 and 27. Crossheads and rams on the top of the upper bracket



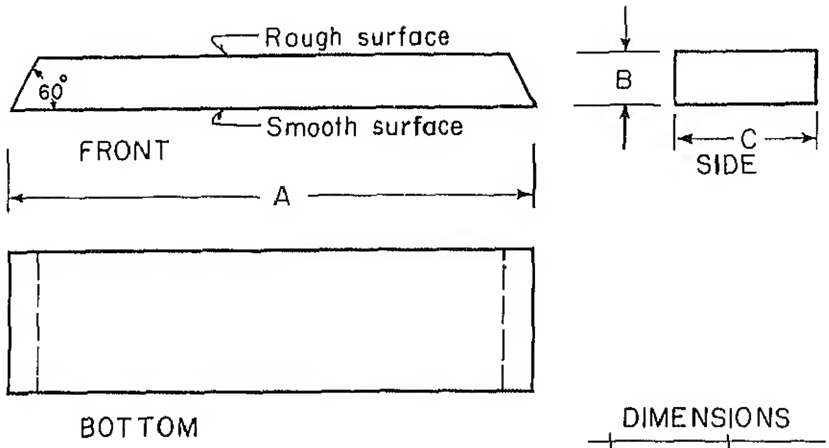
DIMENSIONS

	inches	mm
A	86	2184
B	30	762
C	35	889
D	11	279
E	8	203
F	36	914
G	34	864
H	20	508

REINFORCEMENT

MK	DIAMETER inches	DIAMETER mm
1	1	25
2	1	25
3	½	13
4	½	13
5	½	13

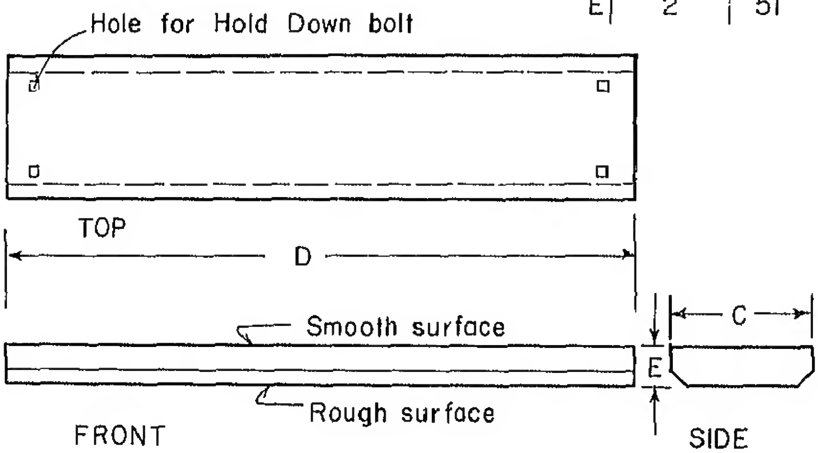
Fig. 24 Dimensions and Reinforcement - Test Brackets for Short-Joint Specimens



(a) UPPER WALL INSERT

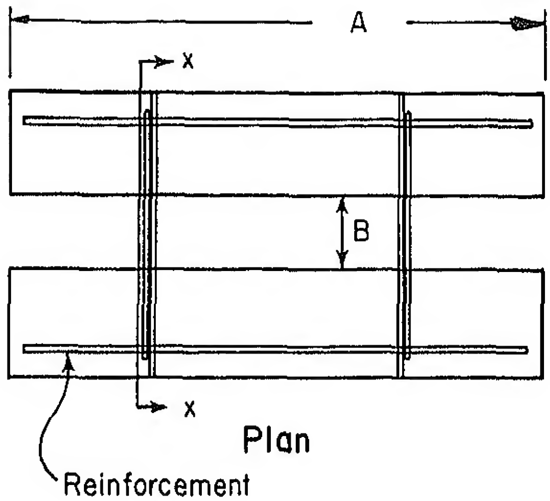
DIMENSIONS

	inches	mm
A	30	762
B	3	76
C	8	203
D	36	914
E	2	51

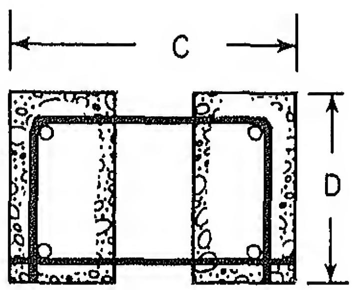


(b) LOWER WALL INSERT

Fig. 25 Wall Inserts - Short-Joint Specimens



Plan



Section xx

Dimensions

	Inches	mm
A	24	610
B	3	76
C	12	305
D	8	203

Fig. 26 Slab Part for Short Joints

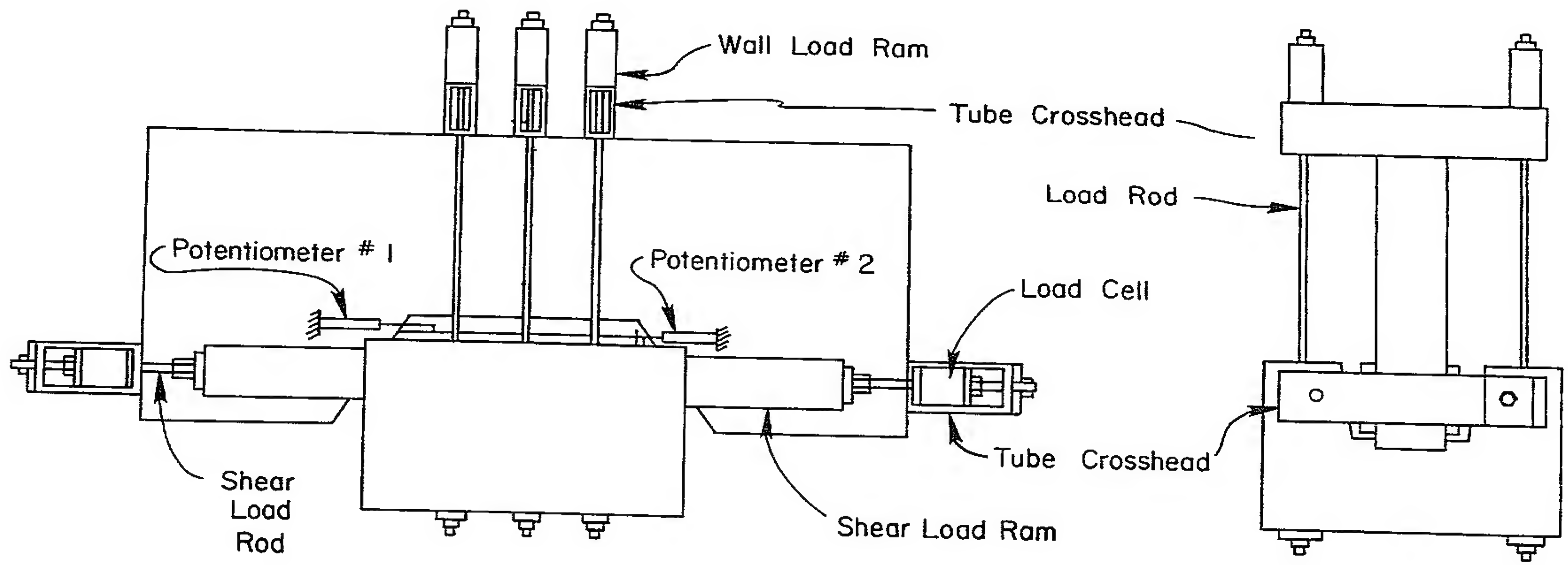


Fig. 27 Test Setup for Short-Joint Specimens

were used to apply vertical wall load. Threaded rods with end nuts and washers were passed through the ram central holes, crossheads and lower-bracket holes to complete the vertical loading system. The six 30-ton (267 kN) rams[7] were connected to a single hydraulic pump for application and maintainance of the desired vertical load.

Equipment for shear loading in both directions also used rods, crossheads and hydraulic rams. Two 60-ton (534 kN) rams with central holes were used for moving the upper bracket in each direction as shown in Fig. 27. Long steel rods passed through the lower bracket holes, through holes in the rams to anchor nuts on steel-tube crossheads at each end of the upper bracket. A nut on the rod at the push end of each ram provided transfer of the ram force to the rod. Shear force was measured via a load cell in the crosshead at each end.

B.2 Materials

Concrete - Concrete used in walls and slabs consisted of Type I cement, Elgin Sand and 3/4-in. (9.5 mm) maximum size aggregate. The concrete was cured in the form under plastic sheets for 7 days after casting. Compressive strength of the concrete was obtained from the average of six 6x12-in. (152 x 304 mm) concrete cylinders tested on the same day as the specimen. The average strengths are shown in Table 6.

Grout - Drypack and fluid grout were made with sand and Type I cement. The drypack contained equal parts of sand and cement by weight. This was mixed with water to produce a cohesive but dry grout. The fluid grout contained three parts of sand to each part of cement by volume. This was mixed at a water-cement ratio of 0.5 to produce a pourable grout. Compressive strength of the fluid grout was obtained from the average of three 6x12-in. (152 x 304 mm) grout cylinders tested on the same day as the specimen. Average strengths are shown in Table 6.

Vertical Tie - High-strength steel rod of 1-in. (25 mm) diameter was used for the vertical tie. The coupler joining the upper and lower parts of the tie was 1-3/4-in. (44 mm) in. diameter and 3-3/4-in. (95 mm) long. Yield strength of the rod as determined by the manufacturer at 0.2% offset is listed in Table 5.

TABLE 6 - MATERIAL PROPERTIES

Specimen Mark	Cylinder Strength, psi*		Vertical Tie Yield, psi
	Wall Concrete	Joint Mortar	
S1	6225	5270	-
R1	5390	6055	-
R2	4280	5220	126,000
R3	5350	5770	-
R4	5170	5440	126,000

*Average of six 6x12-in. cylinders for concrete or three 6x12-in. cylinders for grout. All tested same day as shear testing.

Note: 1 psi = 6.895 kPa

B.3 Instrumentation

Joint Movement - Potentiometers were used to sense joint movements caused by the shear loading. Three potentiometers can be seen in the enlarged test area of the long-joint specimen shown in Fig. 28. Potentiometer No. 1 measured the slip between the floor slab and the upper wall. Potentiometer No. 2 sensed the total sliding movement from lower wall to upper wall. Potentiometer No. 3, at a right angle to the others, measured separation of the joint.

Two potentiometers can also be seen on the short-joint specimen in Figs 7 and 26. Potentiometer No. 1 sensed the sliding movement of the upper wall relative to the floor slab. Potentiometer No. 2 measured slip of the upper wall relative to the lower bracket.

Each potentiometer was connected to the X-axis of an XY recorder to produce a continuous record of displacement.

Load - Shear load on the long-joint specimen was applied by a million pound (4.45MN) testing machine. A potentiometer sensor in the machine's weighing machine was used to produce an electrical output proportional to the applied load. Shear force applied to the short-joint specimens was sensed with load-measuring cells[8]. The electrical output from either the test machine or the load cells was connected to the "Y" axis of each X-Y recorder to produce a continuous load-versus-displacement record during the test.

B.4 Test Procedure

Each test consisted of multiple reversals of shear displacement while a selected wall load was maintained constant. Each loading cycle was controlled to produce a slow, continuous slip of the joint to a selected maximum followed by a slip reversal of selected magnitude. The sliding rate was approximately one inch (25 mm) per minute. Sufficient load was applied to produce the desired sliding rate.

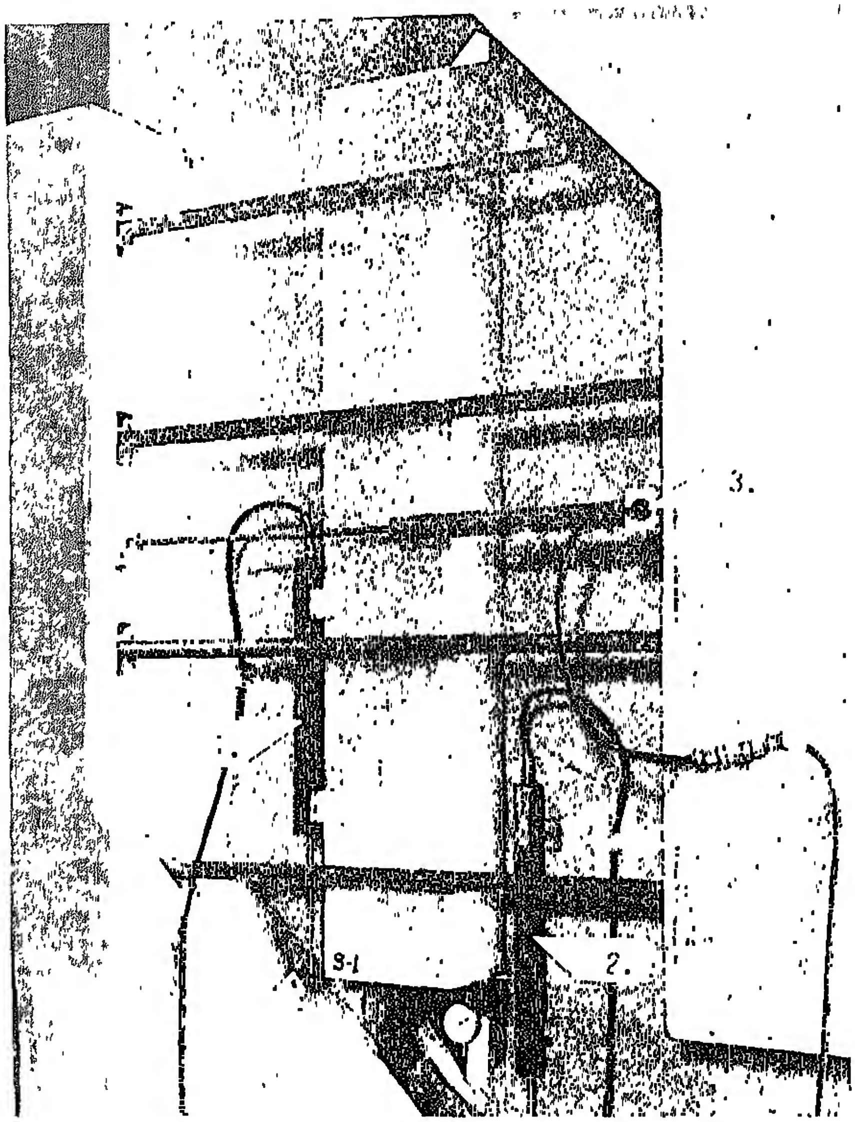


Fig. 28 Instrumentation of Long-Joint Specimen

A planned set of load cycles was applied. This included 3 cycles to 0.1 in. (2.5 mm) in each direction from the original position followed by 9 cycles to 0.2 in. (5.1 mm). Cycles 13 to 15 were to 0.3 in. (7.6 mm) and Cycles 16 and 17 were to 0.5 in (12.7 mm). In some tests, Cycles 14 and 15 were increased to 0.4 in. (10.1 mm) slip and a Cycle 18 was added to 0.6-in. (15.2 mm) slip.

The actual steps necessary for a load cycle were different for the two types of specimen. The long-joint specimen was positioned on end in a large testing machine. In Fig. 6 the "upper wall" is on the left and the "lower wall" is on the right. Each wall part had twin corbels on one end and a single corbel on the other end. The single corbel of one wall was situated in the space between the twin corbels of the other wall. To start a load cycle, loading plates were placed under the lower twin corbel ends and on the base of the testing machine. This raised the specimen so the single corbel on the "lower wall" did not contact the base. Similarly, at the upper end, loading plates were placed on the upper twin corbels and below the test machine load-head. Load applied by the machine moved the "lower wall" downward while the "upper wall" was stationary. The shear load from the test machine was centered on the mid-thickness of the floor slab. After obtaining the desired shear slip, the load was removed and load plates placed on the single corbels to allow loading in the reverse direction. This procedure was repeated for each load cycle. Neoprene rubber pads were placed between the steel loading plates and the specimen surface.

A load cycle on the short-joint specimen was initiated by connecting the hydraulic pump so that the rams extended on one end of the specimen and retracted on the other end. The extension rams pushed against nuts on the loading rods which in turn pulled the crosshead at the far end against the corbel end at the upper wall. When the desired slip movement was attained, the rams were unloaded and the hydraulic connections reversed. The extended rams were retracted while the other rams extended to produce slip movement in the opposite direction. Soft pads were used between the rams and the lower bracket and between the crossheads and the upper bracket. Shear load on the specimen was centered on the mid-thickness of the floor slab.

ACKNOWLEDGEMENTS

This investigation was carried out at the Structural Laboratory of the Portland Cement Association under the direction of Dr. H. G. Russell, Manager, Structural Development Section and Dr. W. G. Corley, Director, Engineering Development Department. Particular credit is due B. Wm. Fullhart, and W. H. Graves, for their assistance in the manufacture and testing of the specimens, and Wm. Hummerich, Jr., for instrumentation. Mr. M. Fintel, Director, Advanced Engineering Services Department, Portland Cement Association was overall project supervisor. Mr. D. M. Schultz, Senior Structural Engineer, Structural Development Section contributed significant direction and advice in the design of test specimens, conduct of the tests and interpretation of data.

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